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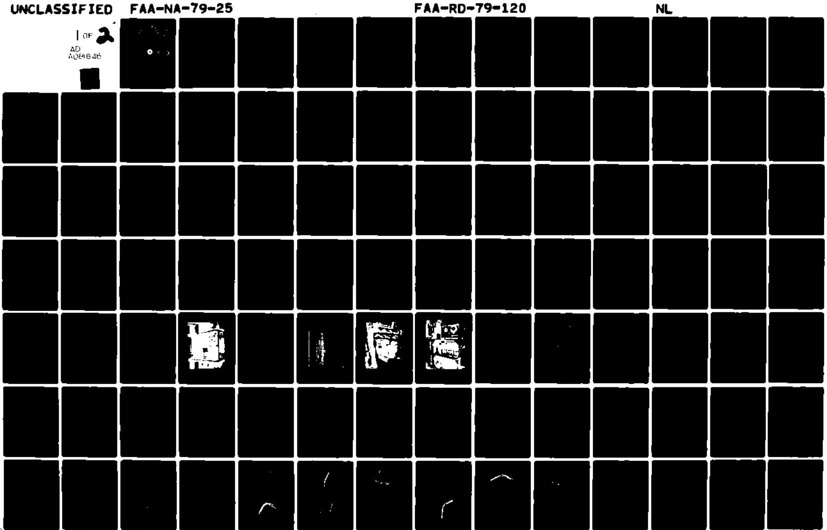

Report No. FAA-RD-79-120

A FLIGHT INVESTIGATION OF SYSTEM ACCURACIES AND OPERATIONAL CAPABILITIES OF A GENERAL AVIATION/ AIR TRANSPORT AREA NAVIGATION SYSTEM (RNAV)

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FEBRUARY 1980

FINAL REPORT

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
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Washington, D.C. 20590

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16. Abstract

Flight tests were conducted at the National Aviation Facilities Experimental Center (NAFEC) using a general aviation/air transport-type area navigation system (RNAV) to investigate area navigation system accuracies and resultant airspace requirements. The system used very high frequency omnidirectional radio range/distance measuring equipment (VOR/DME) radio data for position determination. Data and operational capabilities were also investigated, and graphical data are presented for parallel offsets, delay fans, and turn anticipation. Total system crosstrack standard deviations (1σ) in the en route, terminal, and approach areas were 1.39, 0.46, and 0.25 nautical miles (nmi), respectively.

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METRIC CONVERSION FACTORS

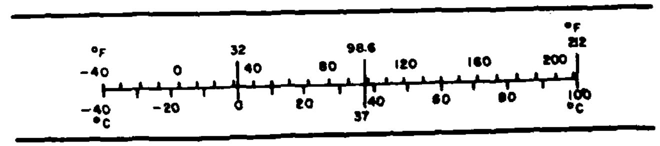
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

PURPOSE.

The purpose of these flight tests was to collect data to be used for the establishment of minimum operational performance standards (MOPS) and to determine the impact of area navigation (RNAV) on the air traffic control (ATC) system. This is one part of an overall program in which 2D, 3D, and 4D RNAV concepts are to be investigated.

BACKGROUND.

The Federal Aviation Administration's (FAA's) interest in RNAV is directed toward the implementation of RNAV routes and operational procedures that will permit navigation in any area within the radiation volume of ground-based very high frequency omnidirectional radio range (VOR) navigation facilities rather than only inbound and outbound radial flight procedures as now used in the present navigation system.

In January 1972, the FAA sponsored an RNAV symposium which highlighted the major operational and technical problem areas that were affecting the immediate implementation and acceptance of RNAV. Based on the intense interest evidenced during the symposium, an FAA/Industry Task Force was established to define how to implement RNAV in the National Airspace System (NAS) in an orderly manner, while at the same time, identifying the payoffs to the ATC system and users. A document entitled, "Application of Area Navigation in the National Airspace System," published in February 1973, defined the way RNAV would be implemented in the NAS and detailed an action plan which included substantial research and development efforts. Previous reports covered other aspects of the action plan while this report deals primarily with the 2D flight test data with some attention given to 3D concepts.

DISCUSSION

RNAV SYSTEM.

The RNAV System selected for these tests is commercially available and is considered to be the type that would primarily be used by air transport and general aviation operators. The system is manufactured by EDO-AIRE, Division of EDO Corporation, Fairfield, New Jersey, and is designated as model TCE71-A. The EDO TCE71-A RNAV system consists of the following components:

1. Navigation Computer Unit (NCU)—accepts VOR, DME, compass heading, altimeter, and true airspeed signals to compute a three-dimensional area navigation path per route leg or approach/departure leg. The computer also provides for slant range correction and provides outputs to an automatic flight control system.

2. Control Display Unit (CDU)—provides pilot-oriented command and advisory (input/output) information. Readout displays, data selectors, and mode provide the pilot with RNAV system status. Figure 1 provides an illustration of the CDU controls.

3. Automatic Data Entry Unit (ADEU)—provides an automatic means of loading up to 20 waypoints with the associated VORTAC frequencies for auto-tuning into the NCU by means of a data card. Figure 1 provides a front view of the ADEU. Figure 2 provides a brief description of the signal path of the EDO RNAV system and associated sensors.

The preprinted data card provides a data field on one side and a reverse side that can be used to print out the actual waypoint and route data to verify the coded data and visualized position. Changes to the card can be made manually on the CDU. Figure 3 provides an example of a preprinted data card.

4. Ancillary Equipments—The following equipment was used with the TCE71-A RNAV system:

a. VOR Navigation Receiver--Bendix RNAV-26C with sine-cosine resolver output,

b. DME-King KDM-7000 or Collins 860E-3,

c. Radio Direction Indicator (RDI)-Sperry RD-100 RDI (figure 4),

d. Air Data Computer--Intercontinental Dynamics Corp. IDC No. 601-18980-002, and

e. Sperry SPI-71 Flight Director System.

Figure 5 shows the installation of the RNAV NCU and ancillary equipments (except RDI) along with the Kennedy model 9832 data recorder in the test aircraft, a Gulfstream 159 (N-48). This aircraft is a twin-engine aircraft with a cruise speed of 220 knots indicated at 10,000 feet (ft) mean sea level (m.s.l.).

FLIGHT TESTS

TEST OBJECTIVES.

The flight test objectives were to:

1. Quantify total RNAV system error using various very high frequency omnidirectional radio range/distance measuring equipment (VOR/DME) radio navigation stations during en route and terminal flight tests.

2. Define the required protected airspace in the en route, terminal, and final approach areas.

3. Quantify flight technical error (FTE).

4. Examine various RNAV operational maneuvers.

5. Examine pilot workload.

6. Examine the effects of turn anticipation.

7. Examine the effects of VOR/DME sensor errors.

ROUTE STRUCTURES.

Three different RNAV routes were constructed to satisfy the broad range of test objectives for this portion of the RNAV avionics investigation program. All flights departed and landed at NAFEC. All flights were coordinated with the New York Air Route Traffic Control Center and/or the Atlantic City Tower.

EN ROUTE FLIGHT TESTS. The route constructed for these tests is shown in figure 6. Waypoint coordinates were formulated at the Sea Isle and the Snow Hill VOR for use as the data flight route. In addition to using Sea Isle and Snow Hill VOR's seven other VOR's in the area were used to fly this route structure. Waypoints were formulated from these seven VOR's to overlay the Sea Isle and Snow Hill VOR's. The station used and the waypoint overlay coordinates are contained in table 1.

FINAL APPROACH FLIGHT TESTS. These routes were constructed to collect final approach data to NAFEC Airport runways 4 and 13 (figures 7 and 8). The Atlantic City (ACY) VOR and other VOR stations were used to study comparative accuracy during the final approach phase of flight. Waypoint coordinates were formulated from four different VOR stations ranging in distance to the missed-approach (MAP) waypoints from 0.5 nautical mile (nmi) up to 24.1 nmi. Table 2 provides a listing of the VOR and waypoint coordinate data for the MAP for runways 4 and 13. These routes were also used to study two types of extended downwind leg patterns. Figures 9 and 10 provide an illustration of these patterns.

STANDARD TERMINAL DEPARTURE AND ARRIVAL FLIGHT TESTS. The Alpha Two (A2) route was constructed by Champlain Technology Industries (CTI) and used in previous RNAV flight tests (Report Nos. FAA-RD-74-209, "Primary Two-Dimensional Area Navigation Terminal Simulation," and FAA-RD-77-1, "A Flight Investigation of System Accuracies and Operational Capabilities of a General Aviation Area Navigation System.") This route was used as one source for operational and flight technical error (FTE) data collection. It was divided into three route segments: A2 Standard Instrument Departure (SID) (figure 11), the A2 Standard Terminal Arrival Route (STAR) (figure 12), and the Final Approach Plates (figure 13) to NAFEC Airport runways 4 and 13.

SCENARIOS.

To satisfy part of the flight test requirements, deviations from the standard route were required to exercise RNAV system capabilities and to experiment with

TABLE 1. RNAV EN ROUTE VOR AND WAYPOINT DATA

VOR STATIONS USED FOR EN ROUTE TESTS

Sea Isle (SIE)—114.80 MHz/10 ft (3 m) m.s.l.
Snow Hill (SWL)—112.40 MHz/40 ft (12.2 m) m.s.l.
Waterloo (ATR)—112.60 MHz/10 ft (3 m) m.s.l.
Baltimore (BAL)—115.10 MHz/140 ft (42.7 m) m.s.l.
Kenton (ENO)—111.40 MHz/10 ft (3 m) m.s.l.
New Castle (EWT)—114.00 MHz/80 ft (24.4 m) m.s.l.
Woodstown (OOD)—112.80 MHz/140 ft (42.7 m) m.s.l.
Nottingham (OTT)—113.70 MHz/210 ft (64 m) m.s.l.
Salisbury (SBY)—114.50 MHz/50 ft (15.2 m) m.s.l.

WAYPOINT COORDINATES DATA

VOR Station	SIE WP Overlay Coords.(°/nmi)	SWL WP Overlay Coords.(°/nmi)	Assigned m.s.l. Altitudes (ft)
SIE	000.0/00*	215.7/69.7	10,000/20,000/ 25,000
SWL	34.3/69.7	000.0/00.0*	20,000/25,000
ATR	57.1/25.7	203.8/46.7	10,000/20,000/ 25,000
BAL	100.4/86.7	147.6/87.3	20,000/25,000
ENO	112.6/34.3	187.0/70.5	10,000/20,000/ 25,000
EWT	141.0/51.5	184.6/97.3	20,000/25,000
OOD	153.1/39.9	193.6/95.0	20,000/25,000
OOT	83.0/93.7	130.5/71.7	20,000/25,000
SBY	44.2/56.0	180.7/17.4	20,000/25,000

*No Slant Range Correction

TABLE 2. RNAV APPROACH VOR AND WAYPOINT DATA

VOR STATION DATA

Atlantic City (ACY)—108.60 MHz/70 ft (21.3 m) m.s.l.

Coyle (CYN)—113.40 MHz/210 ft (64 m) m.s.l.

Millville (MIV)—115.2 MHz/120 ft (36.6 m) m.s.l.

Sea Isle (SIE)—114.80 MHz/10 ft (3 m) m.s.l.

WAYPOINT COORDINATE DATA

VOR Station	MAP-4 WP Coords.(°/nmi)	MAP-13 WP Coords.(°/nmi)	MAP Alts.(ft)
ACY	238.9/.5	316.5/.8	150 (45.7 m)
CYN	207.9/23.1	209.2/22.4	150 (45.7 m)
MIV	116.4/18.5	114.1/18.0	150 (45.7 m)
SIE	34.1/23.5	32.7/24.1	150 (45.7 m)

various operational procedures. Although there were route deviations in the form of extended downwind legs established for the Final Approach test series, the A2 route was designated as the prime route for these deviations. Scenarios were prepared to exercise certain flightpath deviations that might be operationally expected in an ATC environment. The airborne observer was responsible for providing each pilot with the desired scenario event at the proper time. A sample scenario is provided in figure 14. The operational maneuver scenarios include:

PARALLEL OFFSET. This maneuver can be used in lieu of a radar vector. It is one of the EDO RNAV system's capabilities and a projected ATC requirement. The pilot formulates the desired offset message on his CDU, enters it into the computer, then turns the offset mode on when the offset is to be executed. The pilot accomplishes this maneuver by turning approximately 45 degrees (°) toward the parallel offset course and follows this heading until the RDI needle is almost centered. Using turn anticipation, a turn is initiated onto the parallel offset course. He maintains this offset course by keeping the RDI centered. When the pilot is required to return to the parent course, he turns off the offset mode, turns approximately 45° toward the parent course until the RDI needle is almost centered, and then turns onto the parent course.

Part of the requirements of these offset maneuvers was to study the effects of turning inside and outside of a waypoint to a new RNAV route leg and still maintain the correct offset distance through the turn to the next parallel offset course. For example: if the aircraft is on a 5 nmi right offset on a 180° course and the next route leg is a 270° course, the pilot is required to start a right turn inside the waypoint, using turn anticipation, prior to reaching the 5 nmi distance to the offset waypoint. To accomplish this, the pilot is required to closely monitor the DTW display, and at the appropriate distance, switch to the new waypoint, change the OBS to 270°, and start a turn to the right so as to maintain an accurate 5 nmi right offset onto the 270° course. If the aircraft is on a 5 nmi left offset in this same situation, the pilot flies beyond the offset waypoint with the RDI displaying a "FROM" indication and the DTW displaying an increase in distance past this waypoint (outside the waypoint). Prior to reaching 5 nmi past the offset waypoint, the pilot switches to the next waypoint, turns the OBS to 270°, and using turn anticipation, starts a right turn so as to maintain an accurate 5 nmi left offset through the turn and onto the 270° offset course. Figure 14 provides an example of an "outside" offset from a ground track plot.

TURN ANTICIPATION. Turn anticipation can be executed by starting a turn to the next course prior to reaching the upcoming waypoint by using the speed/distance scale recommended in Advisory Circular (AC) 90-45A. It recommends the pilot lead a turn by 1 nmi per hundred knots true airspeed (TAS). This procedure was not a mandatory requirement for these tests. The pilot could formulate his own turn anticipation procedures, as normally used in today's VOR/DME environment.

DIRECT TO WAYPOINT. This was executed by the pilot selecting the desired waypoint he wished to fly direct to from his present position, turning toward this waypoint, and then turning his omnibearing selector (OBS) until the lateral deviation needle on the RDI was zero (centered). This procedure established a new course direct to the selected waypoint.

DELAY FAN. This maneuver is a form of path stretching planned to be used in ATC/RNAV procedures. Two forms of this maneuver were required for these tests. One form was to make a left or right parallel offset maneuver to a specified distance and, upon reaching that distance, turn the offset mode off and execute a "direct to" procedure to the required waypoint. The other form was to make a left or right parallel offset maneuver to a specified distance and maintain the offset to the final approach course before turning the offset mode off and turning onto the final approach course. These path stretching maneuvers are flexible in that ATC can extend the offset distance or cancel the offset prior to the pilot reaching the original offset distance. No parallel offsets were permitted beyond the final approach gate. Figure 15 provides an example of the second form of path stretching from a radar track plot.

VERTICAL NAVIGATION. The pilots were required to fly vertical navigation (VNAV) courses during certain portions of the A2 route and during all final approaches to the runway. Only the operational aspects of VNAV, as they may affect the lateral navigation, are analyzed. The VNAV mode on the EDO RNAV system utilizes barometric-pressure-corrected altitude and along-track distance for its vertical angle computation. The VNAV function is activated by pushing in the VNAV selector on the CDU which functions in both the en route and approach mode. Vertical deviation signals are displayed on the RDI glide slope needle. In the en route mode, full-scale glide slope bar displacement is 600 ft (183 m); and in the approach mode, full-scale displacement is 300 ft (91 m).

There are two VNAV options available to the pilot:

1. He can select his own desired flightpath angle (up to 9°) to reach a desired altitude at the waypoint or at a given distance along his track prior to or beyond the waypoint.

2. He can allow the RNAV system to compute a flightpath angle to a desired altitude at the waypoint or at a given distance along his track prior to or beyond the waypoint.

Once the flightpath angle has been selected and the desired vertical profile start point is intercepted, the glide slope bar will be centered. By keeping the bar centered, the aircraft will follow the selected flightpath angle until the desired altitude is reached. Upon reaching the desired altitude, the flightpath angle becomes 0 (also displayed on the CDU), and the glide slope bar will remain centered if level flight is assumed at this point. The pilot has to anticipate the point along the flightpath angle to start leveling off the aircraft so he will not fly through the selected altitude.

The flightpath angle cannot be prestored for multiple RNAV courses. It has to be selected for the waypoint data currently being used for navigation. If another waypoint is selected before reaching the desired altitude, the selected flightpath angle is cancelled out of the NCU and the pilot must select a new flightpath angle. This second method was the recommended procedure for these tests.

ALONG-TRACK OFFSET. This form of VNAV was required during the Standard Terminal Arrival Route (STAR) portion of the A2 route as part of the VNAV study. Three of the five scenarios required that each pilot make along-track offsets with flightpath angles of approximately 6°, 3°, and 1.5°.

As one of the VNAV capabilities, the pilot can select (using the CDU) a desired flightpath angle to reach a desired altitude at a given distance along his track prior to or beyond a waypoint. Once the desired altitude and flightpath angle has been selected, the pilot flies this path using the glide slope bar indications as outlined in the VNAV section

Since the selected flightpath angle provides VNAV guidance only on the waypoint data currently being used, the pilot must continue using that waypoint until the desired altitude is reached, even though he has passed the waypoint.

If he changes this waypoint data before reaching the desired altitude, the flightpath angle is cancelled out in the NCU, and the pilot will lose computer processed vertical navigation guidance.

This along-track offset capability would most likely be used in a 3D RNAV situation where air traffic control requires an aircraft to be at a specific altitude and at a specific distance before or beyond a designated waypoint for vertical separation from other aircraft at that waypoint.

IMPROMPTU RUNWAY CHANGE. To study the RNAV problems involved in an impromptu runway change, each of the six pilots was given a runway change during one of the A2 route patterns (see sample scenario, table 3). At approximately the same point along the route, each pilot would be told to change his route to runway 13. This required them to reorient their flight planning to another runway which required data for three new waypoints. Three pilots had the required additional 3-waypoint data prestored in the NCU prior to takeoff. The other three pilots would be required to manually load the 3-waypoint data into the NCU after they were told of the runway change.

EXTENDED DOWNWIND LEG. Two methods of extending a downwind leg (path stretching) were part of the final approach flight test series. The recommended RNAV method of accomplishing an extended downwind leg (figure 9) is similar to a radar vector and is performed by utilizing the EDO parallel offset navigation capability. This is done by the pilot entering an offset message into the RNAV computer, including the number of miles he had been instructed to extend downwind. The pilot flies downwind beyond the normal base leg turn waypoint until almost reaching the desired extended distance. After calculating turn anticipation distance, the pilot selects the next waypoint, changes the OBS to the base leg course, turns the offset mode selector on, and starts his turn onto base leg at the desired distance. As the pilot nears the final approach course, he turns off the offset mode and starts his turn onto the final approach course, again using turn anticipation.

The modified method of an extended downwind leg maneuver used in these tests (figure 10) is accomplished by the pilot extending his downwind leg the desired number of miles past the base leg turn waypoint. Upon reaching the desired distance using turn anticipation, the pilot selects the final approach waypoint, turns toward this waypoint, turns his OBS until lateral deviation needle on the RDI is centered to fly direct, and flies this new course to the assigned approach waypoint.

Prior to reaching the original extended downwind distance, ATC can instruct the pilot to increase or decrease the extended downwind distance on either of these maneuvers. Figure 16 provides an example of these maneuvers on a radar track plot.

PILOT SELECTION AND TRAINING.

Six NAFEC project pilots were selected to fly these RNAV tests on the basis of their past experience with the EDO TCE71-A RNAV system.

This previous experience was gained in the GAT-II cockpit simulator. Their EDO experience levels in the GAT-II ranged from 18 up to 45 hours of simulated RNAV time. Each pilot was air transport rated and all were currently rated in the NAFEC Gulfstream 159. Each pilot was assigned to fly a specific number of flight patterns in the three series of flight tests. Table 4 provides a listing of pilot assignments and the total number of data flight patterns completed.

TABLE 3. SAMPLE SCENARIO

1. Make a SID to TANGO and a standard transition to UNIFORM.

2. Prior to reaching UNIFORM, instruct the pilot to descend to 9,500 ft.

3. At the 10-mile DTW VICTOR, instruct the pilot to descend so as to reach 6,500 ft altitude at the 4-mile DTW past VICTOR (1.5° descent). Then continue descent as required.

4. At no later than the 5-mile DTW GOLF, advise the pilot of runway change and reclear him for an RNAV arrival to runway 13 via GOLF direct BALTIC. Cross GOLF at 3,200 ft or above.

5. At the 10-mile DTW BALTIC, instruct the pilot to make a 3-nmi left offset to BALTIC.

6. After passing CAROLINA, make a vertical navigation (VNAV) approach (3°) to MAP-13 using the computed flightpath angle function.

TEST CONDITIONS.

The following test conditions were established to assure as much operational test validity as possible without causing undue flight test delays.

1. The en route tests were to be flown using Instrument Flight Rules (IFR). The final approach and A2 route tests were flown using Visual Flight Rules (VFR).

2. IFR flight plans were filed for each en route flight test. Local VFR flight plans were filed for all other flights.

3. All flights adhered to FAA rules and regulations and to those procedures established by ATC.

4. Each subject pilot was required to perform all RNAV functions, including his own navigation, unless a safety problem occurred.

5. All subject pilots were required to use normal RDI needle deflection sensitivity (2 nmi per dot or ±4 nmi full scale), except during the final approach phase. The final approach RNAV mode provides a RDI needle deflection sensitivity of ±1.0 nmi (0.5 nmi per dot) full scale, which is selectable on the RNAV CDU.

TABLE 4. PILOT FLIGHT TEST ROUTE ASSIGNMENTS AND NUMBER OF TIMES FLOWN

Pilot	(20,000 ft	En Route 25,000 ft	10,000 ft)	Final Approaches	A2 Route
1	—	—		5	5**
2	3	—		5	5
3	—	3		5	5**
4	—	3		5	5
5	3	3	3		5
6	3	—	3		5**
Totals	9	9	6	20	30

— Not Applicable

* Each pattern was considered complete when the pilot passed each of the four waypoints (Flag 1, Sea Isle (SIE), Snow Hill (SWL), and Flag 2).

** These three pilots are required to manually formulate three waypoints for the final approach to runway 13 during scenario 5 (figure 14). These three waypoints were prestored for the other pilots.

TYPICAL FLIGHT TEST PATTERNS.

Figures 14 through 17 are samples of the Extended Area Instrument Radar (EAIR) real-time track plots for each of three flight routes, including some examples of the required operational RNAV maneuvers.

Figure 14 shows an EAIR plot of an A2 pattern in which a scenario was used to execute an "outside" parallel offset during a change to a new route segment leg. Figure 15 presents an EAIR plot of an A2 pattern in which a senario was used for an impromptu runway change maneuver which was made on base leg to the final approach course. A path stretch maneuver was also performed on the flight. Figure 16 shows two EAIR plots of the final approach patterns where a modified and a standard extended downwind leg maneuver were flown. Coyle VOR was used on top pattern and Atlantic City VOR was used on the bottom pattern. Figure 17 illustrates an en route EAIR plot of three patterns (Nos. 4, 5, and 6) made at 25,000 ft m.s.l. while flying waypoints generated from the Baltimore, Woodstown, and New Castle VOR's respectively.

DATA COLLECTION.

A Kennedy 9832 digital tape recorder was used for all pertinent flight data which were recorded at a 2 Hz incremental rate. This flight data consisted of a mixture of analog, digital, and discrete signals which were conditioned and multiplexed by a data acquisition system fabricated at NAFEC. The list of signals recorded in this manner is presented in the appendix.

The radar tracking tape data was collected by NAFEC's EAIR facility. This system is a precision C-band tracking radar with a maximum tracking range of 190 nmi when operated in the beacon tracking mode. This tracking mode was used on all data flights. The EAIR system records a digital output consisting of slant range, azimuth angle, elevation angle, and real time onto a magnetic tape at a 10 Hz rate. EAIR also recorded real time analog track data in Z-Y, X-Y coordinates onto a 30-inch paper plot.

The accuracy of this radar tracking system is 0.2 milliradian in azimuth and elevation and a root mean square (rms) range error not exceeding 20 yards at 3,000 yards per second (yd/s) range rate. During each data flight, an airborne observer recorded information pertinent to the flight on an observer data log.

DATA PROCESSING.

The airborne and ground radar tracking tapes were processed in the following manner. The EAIR raw radar tracking tapes were processed on an International Business Machines (IBM) 7090 computer to generate a binary 7-track tape with 556 bits per inch (bpi) IBM format tape. This tape provided actual aircraft position in latitude, longitude, and altitude referenced to time.

Airborne parameters were obtained from the tape produced on the Kennedy 9832 digital recorder. These tapes were dumped on a line printer and examined after each flight to verify their quality. The tape containing the airborne time referenced parameters was then time merged every 0.5 seconds with the processed EAIR tape. This produced a 9 track 800 BPI time-merged, binary data tape which contained time correlated airborne and ground track measurements. A quick-look printout program was used to further screen this merged data for validity.

After confirming data validity, the merged tapes were examined with a program (SEARCH) which checked pertinent aircraft parameters and flags and recorded any detected changes on the printout. Times of waypoint changes were determined by the use of the SEARCH listings, EAIR plots, merged tape printouts, and observer logs.

Using the merged data tapes and the selected times as inputs, all error values were calculated nominally at 0.1 nmi along each route. These calculated error values, error validity flags, and the data for that sample, were recorded onto a 7-track, 800 bpi parameter tape. Each parameter tape had a header which identified the pattern flown, pilot, copilot, date, and flight test number. Each record on the parameter tape was identified by a segment code and a distance to waypoint. This made it possible to identify and retrieve information from any point on the route. The appendix provides a list of these calculated values. The parameters listed in table A-1 were recorded on the parameter tape at 0.1 nmi increments.

Crosschecking parameter tape printouts, SEARCH printouts, EAIR plots, and observer logs with each other, resulted in start and stop times which bracketed valid portions of segments for error analysis.

DATA ANALYSIS METHODOLOGY.

In analyzing the flight test data collected during these tests, the sources of the possible errors were first identified. This is the same procedure as is indicated in appendix C of 90-45A, dated February 21, 1975. For the horizontal case, there are three errors considered to be components of total system error. However, errors associated with the selection of the desired course using the OBS contribute significantly to the total system error. Therefore, the following errors were considered:

1. Sensor Error (SNCT)--This is the crosstrack error contributed by the ground and airborne sensor elements of VOR and DME.

2. Computer Error (CPCT)--This error includes the error contributed by the RNAV input/output signal conversion equipment and by the computational elements of the RNAV equipment.

3. Flight Technical Errors (FTE)--This error term is a measure of the accuracy with which the pilot controls the aircraft with respect to the commanded position on the displays.

4. OBS Errors (OBSN)--This is the error due to any deviation of the actual OBS setting from the desired setting. It encompasses errors which are human, mechanical, and electrical in nature.

5. Total System Crosstrack Error (TSCT)--This is the measure of the difference between the desired position and actual position of the aircraft.

These error elements in determining aircraft position in space combine, as shown in the error paradigm of figure 18, to form total system crosstrack error. Details of error calculations are contained in the appendix. One very important error term that is not included in this error budget is the blunder. Blunders are gross human errors that can be caused by poor judgement, inattentiveness, or improper system operation caused by erroneous pilot inputs.

The blunder tendency is an extremely important consideration with respect to airspace and system design, but it should be considered separately from the error budget concept since it cannot be treated statistically.

TEST RESULTS

SENSOR ERRORS.

The recorded VOR bearing and DME distance were used to compute sensor errors. This was done by first correcting the VOR bearing for the magnetic variation of the tuned station to give true bearing. The DME distance was converted to ground range by using the aircraft barometric altitude and station elevation. Then, utilizing the true bearing and ground range together with the latitude and longitude of the tuned station, a "sensed" aircraft position was computed. This VOR/DME position was compared to the actual radar tracking position as determined by the EAIR. These differences, oriented on a latitude-longitude coordinate system, were transformed to a coordinate system oriented to the desired track. The new values were sensor crosstrack error (SNCT) and the sensor alongtrack error (SNAT). SNCT and SNAT represented the combined sensor system error, i.e., airborne receivers and VOR stations. These errors were considered valid for analysis whenever valid flags were asserted.

The predominant factor which caused variation in the results for the sensor error was the geometry of the flight tests. Higher tangent point distances (TPD) and along-track distances (see figure 19 for a geometric definition of TPD and ATD) resulted in higher sensor errors.

Table 5 shows the effect of the geometry on the sensor crosstrack and sensor along-track errors. The column labeled VOR Standard Deviation lists the values reported in Report No. FAA-RD-76-113, "An Analysis of Radio Navigation Sensor Accuracies Associated with Area Navigation." The Geometric Index (GI) column in table 5 lists a value which indirectly represents the TPD and ATD for each category of data. The GI was computed by averaging the distance between each waypoint/ground station pair which was utilized for the data collection in each category. The predicted one sigma value for sensor crosstrack error listed in table 5 was computed by taking the product of the sine of the VOR one sigma value times the GI. The predicted value was very close to the measured sensor crosstrack error in each data category.

The 10,000 ft en route data exhibited a relatively low one sigma value for VOR error (1°). This particular case was indicative of how the geometry of the route offset any advantage in the increased accuracy of the chosen ground station.

The approach data were derived from a group of 4 ground stations (listed in table 2) with a GI of 16.7 nmi, while the A2 approach data were derived only from Atlantic City VOR/DME (GI = 3.2 nmi). The measured data showed a two-to-one improvement in sensor crosstrack error (on a one sigma basis) for a ground station which was collocated at the field to which the approaches were made. The corresponding sensor along-track error improvement was five-to-one. These data were also combined to produce summary statistics for the three areas of flight: the en route area, the terminal area, and the final approach area.

TABLE 5. COMPARATIVE STUDY OF SENSOR ERRORS

Data Category	VOR Standard Deviation (degrees)	Geometric Index (nmi)	Predicted One Sigma Sensor Crosstrack Error (nmi)	SNCT One Sigma (nmi)	SNAT One Sigma (nmi)
A2 Approaches (Collocated VOR)	1.5	3.2	0.084	0.149	0.063
Other Approaches	1.5	16.7	0.437	0.333	0.347
Terminal Area	1.7	17.8	0.528	0.456	0.377
En Route 10,000 ft	1.0	42.6	0.743	0.845	0.234
En Route 20-25,000 ft	1.6	59.4	1.659	1.472	1.029

The GI in table 6 for the combined data was computed by taking the average of the values presented in table 5. These summary statistics are presented in table 6. The statistics presented in table 6 include data taken in turns, offsets, straight-line segments, and various other operational maneuvers.

OMNIBEARING SELECTOR (OBS) ERRORS.

A significant contribution to total system error is the OBS setting error. This error varies according to the type of equipment and to the care with which the pilot makes the setting. The effect of this error on the total system error will vary with distance to or from the waypoint being used.

The desired track is described by a vector originating at the "from" waypoint and terminating at the "to" waypoint. The bearing defined by this vector is the desired OBS setting or desired track. Any deviation of the OBS setting will rotate the commanded track away from the desired track. This will introduce a crosstrack error, the magnitude of which depends on the angle between the commanded track and the desired track, as well as the distance to the waypoint along the command track.

In "Preliminary RNAV Avionics Standards," (Report No. FAA-RD-75-178), the OBS crosstrack error is calculated as the product of the distance to waypoint times the angle between the bearing of the desired track and the selected OBS bearing.

$$\text{OBS Error} = \text{DTW} * \alpha \qquad (1)$$

This is an approximation for small angles where $\sin \alpha \approx \alpha$, however, it does not take into account the effect of the added rotation due to FTE which will be negligible except for very large FTE due to blunders.

In figure 20 $|\overline{CD}|$ is the crosstrack error which results when the actual track is rotated from the desired track due to missetting the OBS. The equation to compute the true value of this error is

$$|\overline{CD}| = |\overline{DB}| *\sin \alpha \qquad (2)$$

One must note, however, that F in figure 20 is the aircraft position as presented by the RNAV computer, and the assumed aircraft position for purposes of simplification. Therefore, the DTW presented by the computer is $|\overline{FB}|$. If DTW $|\overline{FB}|$ is substituted into equation 1, it is obvious that the value obtained for OBS error will be different from the true value given by equation 2. The difference between the two results will be proportional to the difference between $|\overline{DB}|$ and $|\overline{FB}|$ and the difference between these two quantities will only be zero when $|\overline{FE}|$ (flight technical error by definition) is zero. Likewise, there is a difference between the flight technical error $|\overline{FE}|$ displayed to the pilot and referenced to the rotated track $|\overline{DB}|$ and the flight technical error $|\overline{FD}|$ when referenced to the desired track $|\overline{AB}|$. It is evident, therefore, that when using a simplified analysis, there will be some interplay and contamination between FTE and OBS error.

TABLE 6. SENSOR ERROR SUMMARY STATISTICS

Data Category Area	GI	Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
En Route	51.0	SNCT	15,436	0.220	1.375
		SNAT	15,436	-0.282	0.919
Terminal	17.8	SNCT	23,569	-0.037	0.456
		SNAT	23,569	-0.137	0.377
Approach	9.95	SNCT	3,318	-0.177	0.228
		SNAT	3,318	-0.063	0.197

To give some idea of the magnitude of these errors, typical values were substituted for the orthogonal projection of distance to waypoint (DTW) (40 nmi), OBS angular error (2.1°), and FTE (0.6 nmi). The difference between using equation 1 versus equation 2 to calculate OBS error is about 8 ft. Likewise, the difference between FTE as displayed to the pilot (referenced to the rotated track) and the FTE referenced to the desired track is about 2.5 ft. For differences of such small magnitude, the interplay between FTE and OBS error was disregarded.

The original formula utilizing the DTW was slightly modified by using the sine of the angular error rather than the small angle approximation. The modified equation used in this analysis was:

OBSN = DTW *SIN α
= ACTUAL OBS ANGLE—DESIRED TRACK ANGLE

OBS errors were calculated in nautical miles at each 0.1 nmi increment along the test routes, except when the pilot was in the act of resetting the OBS. Angular OBS errors were also calculated as the measured error between the desired course and the set course at the beginning of each leg of the test route. Any deviation greater than 15° was rejected as a pilot blunder.

On these tests, the OBS setting function was controlled by a course select knob which positioned a course arrow against a compass card on the RDI. Although the resolution on the compass card was in 5° increments, the RDI had a digital course indicator which allowed the pilot to accurately set the OBS to the nearest degree. When the RNAV course required OBS settings of degrees and tenths degrees, the pilot used his own estimation in setting the last OBS digit to the nearest required tenth degree or he rounded off the setting to the nearest degree. The OBS error was examined in the en route area, in the terminal area, and in the approach area. Table 7 enumerates the statistics for those three flight areas.

TABLE 7. OBS ERROR STATISTICS VERSUS FLIGHT AREA

Area		OBS Error (degrees)		OBS Error (nmi)
Flight Area	Mean	One Standard Deviation	Mean	One Standard Deviation
Approach	1.259	0.279	-0.062	0.038
Terminal	0.880	1.219	-0.131	0.112
En Route	0.725	0.673	-0.425	0.400

The OBS angular error (degrees) was a direct measure of the accuracy with which the pilots set the OBS, as well as the accuracy of the instrument itself. The results showed that greatest variability in setting the OBS occurred in the terminal area. This was due to the relative complexity of the various scenarios employed during the A2 pattern tests which increased the overall pilot workload, as well as the variety of settings required by each pilot.

The bias errors (mean) in the OBS angular error indicated an error source which is electromechanical in nature. The course arrow and the digital OBS readout may not have been mechanically zeroed or there may have been a slippage between mechanical zero and electrical zero. These statistics also showed the effects of segment length on the OBS crosstrack error (nmi).

Even though the angular standard deviation was about twice as high in the terminal area as it was in the en route area, the terminal area OBS crosstrack error standard deviation was less than that measured in the en route area.

RNAV COMPUTER ERRORS.

The TCE-71A presented position information as a magnetic bearing to the waypoints (BTW) and DTW. By correcting the BTW for magnetic variation and converting BTW to a true bearing, the BTW and DTW were converted to a latitude and longitude which represented the aircraft position as calculated by the RNAV computer. The RNAV computer position was compared to the sensed position (VOR/DME) and then rotated from the latitude-longitude coordinate system to a coordinate system oriented along the desired track. After rotation, these differences were the computer along-track error (CPAT) and CPCT. Computer errors were considered valid for the analysis whenever the correct waypoint coordinates were selected and valid sensor flags and a valid RNAV computer status were asserted. The CPCT error data were found to be correlated with the SNCT error data. This was not surprising in light of the signal processing performed in the TCE-71A. The computation is basically the solution to a typical VOR/DME/air data navigation problem. Additionally, digital filtering and wind modeling techniques are applied to enhance the position determination capability. Also, since the computer position was presented as an angle (BTW) and a distance (DTW), the variability of the computer error could be expected to increase as segment lengths increased.

Both the computer error data correlation with sensor error data and the nature of the computer position information are offered as explanations for the increasing trend in computer errors clearly evident in table 8. The data included not only straight-line segments, but also data taken in turns, offsets, and various operational maneuvers. Nonslant range corrected data were not included.

TABLE 8. RNAV COMPUTER ERROR STATISTICS

Flight Area	Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
Approach	CPCT	3,318	0.010	0.147
	CPAT	3,318	0.060	0.213
Terminal	CPCT	23,569	0.021	0.366
	CPAT	23,569	0.028	0.277
En Route	CPCT	11,262	-0.227	0.826
	CPAT	11,262	-0.314	0.823

FLIGHT TECHNICAL ERROR.

FTE is the measure of the pilot's ability to fly the commanded track. Therefore, the crosstrack information which was presented to the pilot on the RDI was recorded directly as a voltage and scaled appropriately (FTE=RDI deflection * scale factor). This was the value used for all subsequent analyses involving crosstrack distances. As was mentioned in the OBS Error Section, this would not be a true crosstrack distance due to any rotation of the commanded track with respect to the desired track. However, this choice provides an adequate measure of the human factor.

To insure that pilot ability was fairly represented, FTE was only considered once the pilot had established himself in a steady-state condition on the new track. Each segment was considered on an individual basis. Aircraft parameters were carefully examined along with radar tracking plots and observer logs to determine the portions considered to be valid for the FTE data analysis. No turn data were included.

FTE was expected to vary as a function of: waypoint storage capacity and resultant workload, pilot experience level, display sensitivity, pilot awareness, and individual pilot skill and technique. The data were examined on an individual basis for each of the subject pilots who were all considered to be highly experienced. As evidenced by the statistics presented in table 9, there was little variability between individual pilots. These statistics represent data taken during the A2 pattern approaches to runway 13 and 4. These approaches were chosen as the best test of the individual ability of each of the six subject pilots, since variation of the other factors was minimized.

There were no meaningful data available to analyze FTE as a function of waypoint storage capacity. This was because during the impromptu runway change on the A2 pattern, where this variation would be evidenced, two of the three pilots who flew with reduced waypoint storage capacity made blunder errors.

The statistics presented in table 10 showed that there was a slight decrease in the standard deviation of FTE between the en route area data and the terminal area data which may be attributed to increased pilot awareness in the terminal area.

During the final approaches, all subjects were required to use the approach mode of the RNAV system. This feature increased the course width sensitivity by a factor of 4 from ± 4 nmi to ± 1 nmi full-scale sensitivity. There was a significant decrease in the standard deviation of FTE between the en route/terminal area data and the approach area data. The fourfold increase in the sensitivity of the course width in the approach mode enabled the pilots to reduce the FTE standard deviation by a factor of 3.

TABLE 9. FLIGHT TECHNICAL ERROR VERSUS INDIVIDUAL PILOT

Pilot	Samples	Mean (nmi)	One Standard Deviation (nmi)
1	297	-0.028	0.179
2	161	-0.106	0.204
3	277	-0.057	0.133
4	375	-0.052	0.152
5	469	0.024	0.199
6	381	0.006	0.184

FLIGHT DIRECTOR TO RNAV SYSTEM INTERFACE PROBLEMS.

The EDO TCE71 RNAV computer has two sets of horizontal and vertical deviation outputs. Both are direct current (d.c.) signals directly proportional to deviation. One set is of a magnitude compatible with RDI instruments, that is, ±150 μA into 1 kΩ (1,000 ohm). The other set is intended to drive an Automatic Flight Control System (AFCS) and has a ±2 volt (V) maximum with 100 milliampere (mA) current capability.

The Sperry SPI-71 Flight Director was not designed with RNAV capability. The system does not accept the high level AFCS signals from the RNAV computer, so the standard RDI signals were used. The scale factors of these signals are ±4 nmi full-scale horizontal and ±600 ft vertical.

To obtain vertical guidance presentation, it was necessary to operate the flight director in its "approach" mode. This causes no gross problems in the vertical guidance, since the RNAV vertical course width of 1,200 ft is equivalent to a glide slope's 1.4° course width (Atlantic City runway 13 ILS is the example) at a distance of 8 nmi from threshold. The vertical signal input was thus within the range expected by the flight director.

However, the RNAV horizontal course width of 8 nmi was equivalent to a localizer's 3.5° course width at a distance of 130 nmi from threshold. This situation produced extreme sluggishness in the flight director roll commands to the point of unusability. Feeding the AFCS output, suitably limited to avoid damage to the roll computer input circuits, into the flight director horizontal channel did improve the situation, but it was still not optimum. Further improvement could be realized by changing the RNAV computer's internal AFCS scale factors.

Two minor problems occurred when changing waypoints or flight path angles (FPA's). While stabilized on a straight leg, the flight director computed and stored crosswind components. When changing legs on an RNAV route, the actual crosswinds changed rapidly while the aircraft was turning, but the flight director was slow to recompute the new crosswind component and gave slightly biased horizontal commands for a few miles into the new leg. The actual error was dependent on winds, turn angle, and aircraft speed, but it seemed to be no more than 0.5 mile crosstrack.

When changing FPA's during descent, the flight director apparently interpreted a change in vertical deviation rate without a corresponding change in aircraft rate of descent as a bend or reflection in a glide slope beam and thus ignored the new FPA for 15 to 30 seconds. Guidance was good after this transition.

The SPI-71 does not give vertical guidance during ascent on fixed flightpath angles greater than approximately 1° in the approach mode. The flight director apparently expects to intercept the glide slope from below as the beam descends, and so does not give any strong fly-up commands.

These problems occurred only when using RNAV inputs to the flight director. The SPI-71 continued to function satisfactorily on normal ILS or VOR signals.

TABLE 10. FLIGHT TECHNICAL ERROR SUMMARY STATISTICS

Area	Samples	Mean (nmi)	One Standard Deviation (nmi)
En Route	14,340	-0.160	0.671
Terminal	18,505	-0.158	0.544
En Route (Combined)	32,845	-0.158	0.603
Approach	2,757	-0.019	0.189

TOTAL SYSTEM ERROR AND ERROR BUDGET.

The most important factor in the analysis of RNAV systems is the total system error. This total system error figure determines the requirements for the needed amount of protected airspace in NAS. Two methods of determining this figure are to measure it in actual flight tests or to identify and measure the error components of the total system error and calculate it. Both methods were used in these tests.

TSCT was the difference between the desired position of the aircraft on a track and the actual position of the aircraft. The actual position of the aircraft was defined as the position recorded by the EAIR. The desired position was defined as the orthogonal projection of the actual position onto the desired track. Choosing these definitions fixed the total system along-track error (TSAT) as zero. Total system crosstrack error was a composite of all the other errors, as shown in the error paradigm figure 18.

TSCT = Desired Position--Actual Position
TSCT = FTE + SNCT + OBSN + CPCT
TSAT = 0

Sample sizes for individual error component statistics that were listed in previous sections of this report were not equal for a given flight area. This was because data for FTE and omnibearing selector navigation (OBSN) were taken during steady-state conditions while data for SNCT and CPCT were taken over all portions of segments, including turns.

Also, certain operational maneuvers prohibited pooling of certain individual error components. In the en route area, the nonslant range corrected computer error data were not included; in the terminal area, the OBS error data for the "direct to" segment (VICTOR direct to HOTEL) in scenario 2 on the A2 pattern were not included. In both of these cases, TSCT data were also excluded from the summary statistics. These summary statistics are presented in table 11. The values listed represent actual TSCT for the three flight areas.

TABLE 11. TOTAL SYSTEM ERROR SUMMARY STATISTICS

Area	Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
Approach	SNCT	3,318	-0.177	0.228
	CPCT	3,318	0.010	0.147
	FTE	2,757	-0.019	0.189
	OBSN	2.747	-0.062	0.038
	TSCT	2,757	-0.234	0.260
Terminal	SNCT	23,569	-0.037	0.456
	CPCT	23,569	0.021	0.366
	FTE	18,505	-0.158	0.544
	OBSN	17,567	-0.131	0.112
	TSCT	17,573	-0.302	0.459
En Route	SNCT	15,436	0.220	1.375
	CPCT	11,262	-0.227	0.826
	FTE	14,340	-0.160	0.671
	OBSN	14,336	-0.425	0.400
	TSCT	10,606	-0.272	1.390

The root sum square (rss) method, as decribed in AC-90-45A, was used to calculate TSCT for this report. To faciliate this computation the statistics presented in table 12 were prepared. The data for this summary were taken in the steady-state case, and no data were taken in turns or in operational maneuvers. Also, the data were "paired" data; that is, the sample size of TSCT and all the error components were equal, and each sample represented a set of data where all components were valid and were measured at the same time. It will be noted, therefore, that the sample sizes listed in table 11 were in most cases larger than the sample sizes listed for the paired data in table 12. The means and standard deviations were only slightly different (hundredths of nautical miles) because of the different sample sizes.

Table 13 compares the measured value of TSCT against the value of TSCT calculated from the error components of table 12. The calculated value was computed using the rss method. In each case the rss calculated value was a more conservative estimate of crosstrack error in comparison to the measured value of TSCT. To graphically illustrate how the individual error components combined to form TSCT, in a statistical sense, histograms were plotted for SNCT, CPCT, FTE, OBSN, and TSCT. The histograms were generated from the same paired data used for the rss calculations. Each histogram plot was overlayed with its own normal density function.

These plots are presented in figures 21 through 35. To more thoroughly examine the relationship between TSCT and the components that make it up, a stepwise multiple regression was run on the paired data. Stepwise multiple regression

TABLE 12. TOTAL SYSTEM ERROR PAIRED DATA SUMMARY STATISTICS

Area	Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
Approach	SNCT	2,966	-0.176	0.222
	CPCT	2,966	0.009	0.141
	FTE	2,966	-0.012	0.188
	OBSN	2,966	-0.060	0.039
	TSCT	2,966	-0.229	0.251
Terminal	SNCT	17,662	-0.033	0.439
	CPCT	17,662	0.005	0.343
	FTE	17,662	-0.161	0.540
	OBSN	17,662	-0.131	0.113
	TSCT	17,662	-0.302	0.459
En Route	SNCT	10,599	0.444	1.396
	CPCT	10,599	0.246	0.805
	FTE	10,599	-0.182	0.632
	OBSN	10,599	-0.390	0.392
	TSCT	10,599	-0.275	1.391

TABLE 13. COMPARISON OF MEASURED AND RSS-CALCULATED TOTAL SYSTEM ERROR STATISTICS

Area	Measured TSCT One Standard Deviation (nmi)	RSS-Calculated TSCT One Standard Deviation (nmi)
Approach	0.251	0.326
Terminal	0.459	0.784
En Route	1.391	1.775

TABLE 14. APPROACH AREA DATA CORRELATION MATRIX

	TSCT	SNCT	CPCT	FTE	OBSN
TSCT	1.0000	0.4740	0.2385	0.5314	0.2529
SNCT	0.4740	1.0000	-0.4212	-0.2838	0.2874
CPCT	0.2385	-0.4212	1.0000	0.0920	-0.0094
FTE	0.5314	-0.2838	0.0920	1.0000	-0.1467
OBSN	0.2529	0.2874	-0.0994	-0.1467	1.0000

TABLE 15. TERMINAL AREA DATA CORRELATION MATRIX

	TSCT	SNCT	CPCT	FTE	OBSN
TSCT	1.0000	0.0782	0.0725	0.6935	0.1158
SNCT	0.0782	1.0000	-0.5544	-0.3793	0.1108
CPCT	0.0725	-0.5544	1.0000	-0.0800	-0.0827
FTE	0.6935	-0.3793	-0.0800	1.0000	-0.2150
OBSN	0.1158	0.1108	-0.0827	-0.2150	1.0000

TABLE 16. EN ROUTE AREA DATA CORRELATION MATRIX

	TSCT	SNCT	CPCT	FTE	OBSN
TSCT	1.0000	0.6836	-0.0850	0.3438	0.4042
SNCT	0.6838	1.0000	-0.6374	-0.1624	0.2465
CPCT	-0.0850	-0.6374	1.0000	0.0883	0.1246
FTE	0.3438	-0.1624	0.0883	1.0000	-0.1469
OBSN	0.4042	0.2475	0.1246	-0.1469	1.0000

is a statistical technique for analyzing a relationship between a dependent variable, TSCT, and a set of assumed independent variables, SNCT, CPCT, FTE, and OBS errors, and for selecting the independent variables in the order of their importance. The criterion of importance is based on the reduction of sums of squares, and the independent variable most important in this reduction in a given step is entered in the regression.

The stepwise regression allows any variable in the original set to be used as the dependent variable. For the purposes of this analysis, TSCT was used as the dependent variable.

A correlation matrix was also computed for the paired data. Tables 14, 15, and 16 represent the correlation matrices for the approach area data, the terminal area data, and for the en route area data, respectively. In the approach area, SNCT and FTE showed moderate correlation with TSCT, while CPCT and OBS error showed weaker correlation. In the terminal area, FTE was highly correlated with TSCT, while the remaining error components, SNCT, CPCT, and OBSN showed virtually no correlation with TSCT. In the en route area, SNCT showed a high correlation with TSCT and OBS, while FTE showed moderate correlation with TSCT, and CPCT showed virtually no correlation with TSCT.

The results of the regression analysis are presented in tables 17 and 18; table 19 shows the approach, terminal, and en route data. The error components identified in their order of significance for both the terminal area data and the approach area data were FTE, SNCT, CPCT, and OBSN. For the en route area data, the order of significance was SNCT, FTE, CPCT, and OBSN. This exchange in order of significance between SNCT and FTE was probably due to an increase in the GI in the en route area as compared to the terminal and approach areas.

APPLICATION OF WAYPOINT STORAGE.

The TCE71-A RNAV system can store up to 20 waypoints at a time and has a two-digit waypoint number display for waypoints 1 through 99. Waypoint data can be loaded into the NCU either manually with the CDU or automatically with a preprinted waypoint data card through the ADEU. To manually load one waypoint data into the NCU requires up to 25 knob, switch, and push-button selections. It requires four additional selections to verify the accuracy of the waypoint loaded into the NCU.

A test subject with approximately 10 hours of "hands-on" experience with the CDU was timed while loading each of the 10 waypoint data used in the A2 route tests. These timing tests were made in the G-159 aircraft while it was parked on the ramp. The subject s waypoint loading and vertification times ranged from 29 seconds up to 40 seconds per waypoint. Three loading errors were made by the subject during this test. This timing test was made during the shakedown phase of RNAV testing.

It was initially determined that preprinted flight plan data cards would be used for the en route and final approach phase of flight testing. Only the

TABLE 17. STEPWISE MULTIPLE REGRESSION ANALYSIS FOR APPROACH AREA DATA

STEP 1

Variable Entered = FTE

Sum of squares reduced in this step = 52.659
Proportion reduced in this step = 0.282

Cumulative sum of squares reduced = 52.659
Cumulative proportion reduced = 0.282 of 186.461

For one variable entered
Multiple correlation coefficient = 0.531
(Adjusted for D.F.) = 0.531
Standard error of estimate = 0.212
(Adjusted for D.F.) = 0.212

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
FTE	+0.70785	0.02073	+34.154
Intercept	-0.22029		

STEP 2

Variable Entered = SNCT

Sum of squares reduced in this step = 79.171
Proportion reduced in this step = 0.425

Cumulative sum of squares reduced =131.830
Cumulative proportion reduced = 0.707 of 186.461

For two variables entered
Multiple correlation coefficient = 0.841
(Adjusted for D.F.) = 0.841
Standard error of estimate = 0.136
(Adjusted for D.F.) = 0.136

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
FTE	+0.96472	0.01381	+69.840
SNCT	0.76625	0.01169	65.528
Intercept	-0.08246		

STEP 3

Variable Entered = CPCT

Sum of squares reduced in this step = 47.613
Proportion reduced in this step = 0.255

Cumulative sum of squares reduced =179.443
Cumulative proportion reduced = 0.962 of 186.461

For three variables entered
Multiple correlation coefficient = 0.981
(Adjusted for D.F.) = 0.981
Standard error of estimate = 0.049
(Adjusted for D.F.) = 0.049

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
FTE	+0.98693	0.00495	+199.207
SNCT	1.03635	0.00460	225.066
CPCT	0.99307	0.00701	141.755
Intercept	-0.04340		

STEP 4

Variable Entered = OBSN

Sum of squares reduced in this step = 4.774
Proportion reduced in this step = 0.026

Cumulative sum of squares reduced =184.217
Cumulative proportion reduced = 0.988 of 186.461

For four variables entered
Multiple correlation coefficient = 0.944
(Adjusted for D.F.) = 0.944
Standard error of estimate = 0.028
(Adjusted for D.F.) = 0.028

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
FTE	+1.00259	0.00281	+356.892
SNCT	0.98390	0.00269	366.166
CPCT	0.98591	0.00396	248.746
OBSN	1.06645	0.01344	79.355
Intercept	0.01111		

TABLE 18. STEPWISE MULTIPLE REGRESSION ANALYSIS FOR TERMINAL AREA DATA

STEP 1

Variable Entered = FTE

Sum of squares reduced in this step = 1,789.861
Proportion reduced in this step = 0.481

Cumulative sum of squares reduced = 1,789.861
Cumulative proportion reduced = 0.481 of 3,722.134

For one variable entered
Multiple correlation coefficient = 0.693
(Adjusted for D.F.) = 0.693
Standard error of estimate = 0.331
(Adjusted for D.F.) = 0.331

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
FTE	0.58980	0.00461	127.900
Intercept	-0.20752		

STEP 2

Variable Entered = SNCT

Sum of squares reduced in this step = 506.240
Proportion reduced in this step = 0.136

Cumulative sum of squares reduced = 2,296.101
Cumulative proportion reduced = 0.617 of 3,722.134

For two variables entered
Multiple correlation coefficient = 0.785
(Adjusted for D.F.) = 0.785
Standard error of estimate = 0.284
(Adjusted for D.F.) = 0.284

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
FTE	0.71338	0.00428	167.784
SNCT	0.41720	0.00527	79.177
Intercept	-0.17296		

STEP 3

Variable Entered = CPCT

Sum of squares reduced in this step = 816.395
Proportion reduced in this step = 0.219

Cumulative sum of squares reduced = 3,112.496
Cumulative proportion reduced = 0.836 of 3,722.134

For three variables entered
Multiple correlation coefficient = 0.914
(Adjusted for D.F.) = 0.914
Standard error of estimate = 0.186
(Adjusted for D.F.) = 0.186

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
FTE	0.89358	0.00302	295.642
SNCT	0.85154	0.00446	191.137
CPCT	0.81356	0.00529	153.775
Intercept	-0.13443		

STEP 4

Variable Entered = OBSN

Sum of squares reduced in this step = 359.799
Proportion reduced in this step = 0.097

Cumulative sum of squares reduced = 3,472.295
Cumulative proportion reduced = 0.933 of 3,722.134

For four variables entered
Multiple correlation coefficient = 0.966
(Adjusted for D.F.) = 0.966
Standard error of estimate = 0.119
(Adjusted for D.F.) = 0.119

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
FTE	0.9665	0.00198	485.211
SNCT	0.87090	0.00285	305.075
CPCT	0.87127	0.00341	255.784
OBSN	1.30460	0.00818	159.462
Intercept	0.04818		

TABLE 19. STEPWISE MULTIPLE REGRESSION ANALYSIS FOR EN ROUTE AREA DATA

STEP 1

Variable Entered = SNCT

Sum of squares reduced in this step	=	9,583.860
Proportion reduced in this step	=	0.467
Cumulative sum of squares reduced	=	9,583.860
Cumulative proportion reduced	=	0.467 of 20,507.187

For one variable entered

Multiple correlation coefficient	=	0.684
(Adjusted for D.F.)	=	0.684
Standard error of estimate	=	1.015
(Adjusted for D.F.)	=	1.015

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
SNCT	0.68102	0.00706	96.424
Intercept	-0.57722		

STEP 2

Variable Entered = FTE

Sum of squares reduced in this step	=	4,356.118
Proportion reduced in this step	=	0.212
Cumulative sum of squares reduced	=	13,939.979
Cumulative proportion reduced	=	0.680 of 20,507.187

For two variables entered

Multiple correlation coefficient	=	0.824
(Adjusted for D.F.)	=	0.824
Standard error of estimate	=	0.787
(Adjusted for D.F.)	=	0.787

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
SNCT	0.75659	0.00555	136.315
FTE	1.02843	0.01227	83.836
Intercept	-0.42321		

STEP 3

Variable Entered = CPCT

Sum of squares reduced in this step	=	4,424.662
Proportion reduced in this step	=	0.216
Cumulative sum of squares reduced	=	18,364.641
Cumulative proportion reduced	=	0.896 of 20,507.187

For three variables entered

Multiple correlation coefficient	=	0.946
(Adjusted for D.F.)	=	0.946
Standard error of estimate	=	0.450
(Adjusted for D.F.)	=	0.450

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
SNCT	1.14097	0.00410	278.336
FTE	1.04918	0.00701	149.701
CPCT	1.04168	0.00704	147.919
Intercept	-0.33383		

STEP 4

Variable Entered = OBSN

Sum of squares reduced in this step	=	345.356
Proportion reduced in this step	=	0.017
Cumulative sum of squares reduced	=	18,709.996
Cumulative proportion reduced	=	0.912 of 20,507.187

For four variables entered

Multiple correlation coefficient	=	0.955
(Adjusted for D.F.)	=	0.955
Standard error of estimate	=	0.412
(Adjusted for D.F.)	=	0.412

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
SNCT	1.06376	0.00413	257.813
FTE	1.08196	0.00646	167.482
CPCT	0.92273	0.00697	132.425
OBSN	0.51731	0.01147	45.120
Intercept	-0.12120		

route A2 (SID/STAR) flights would require manual waypoint loading by the subject pilot to study pilot workload. Two pilots would be restricted to a three-waypoint capability, two pilots to a six-waypoint capability, and two pilots to a ten-waypoint capability. The first attempt to fly the A2 route using a three-waypoint capability was flown by the RNAV project pilot. After flying three patterns, the project pilot recommended that the copilot assist in the manual waypoint loading. He reported that the distraction from other essential flight duties was too extensive while manually loading a waypoint. He felt it was potentially hazardous for the subject pilot to perform this function in a G-159 which is a two-pilot aircraft. The airborne observer concurred that this pilot encountered difficulty in staying on course while loading waypoints into the NCU.

As a result of the initial flights, the pilot workload study of manual loading of waypoints was modified. The tests were changed to use preprinted waypoint data cards that were loaded into the NCU prior to takeoff, except the A2 route. Three of the subject pilots had the 10, A2 route waypoints to NAFEC runway 4 plus the three additional waypoints to runway 13 (impromptu runway change), preloaded by cards, prior to departure. The other three subject pilots had the 10 waypoints to runway 4 preloaded by card but were required to manually load the three additional waypoints to runway 13 when they were given an impromptu runway change (scenario 5 shown in figure 13). The use of preprinted waypoint data cards almost eliminated the pilot workload of loading waypoints into computer storage. These cards were reused for each change of subject pilots. The data cards were simple to load into the NCU, and once these data were verified as correct on the first flight, there was no need to verify them on the remaining flight tests. This verification was done each time to validate reliability. It required approximately 30 seconds to load and store a preprinted data card with up to 20 waypoints on it.

PILOT WORKLOAD.

Using conventional navigation methods (point-to-point VOR/DME and radar vectors), pilot workload is normally at its lowest during en route navigation. Pilot workload can be expected to increase while transitioning from the en route to the terminal airspace, i.e., altitude changes, speed control, handoffs, increased pilot/ATC communications, and vectoring for metering and spacing into the terminal airspace and onto the final approach course. The highest pilot workload levels can be expected during the takeoff and landing phase, including a period shortly after takeoff and on the approach to a landing. The reduced amount of airspace and the need for "funneling" aircraft to the final approach course contribute to this increased workload.

One of the objectives of these tests was to investigate pilot workload when RNAV systems and concepts were applied in NAS. As mentioned earlier in this report, a determination was made to use preprinted waypoint data cards for loading waypoint data into the NCU for all flight test phases. The exception was that three pilots were required to manually load three waypoints each during an impromptu runway change. These preprinted waypoint data cards eliminated a great deal of pilot workload during preflight as well as inflight.

The pilots sometimes had difficulty in associating the waypoint name on their RNAV charts with the waypoint number displayed on the CDU during flight. This caused the pilots to make numerous references to their charts and the OBS setting to correlate the waypoint number with the chart waypoint name to maintain position orientation during the flight. Doing this often distracted or delayed them in performing other flight duties. Much of this waypoint correlation problem was reduced when the pilots marked their RNAV charts with the CDU waypoint numbers associated with the chart waypoint names.

EN ROUTE PILOT WORKLOAD. The use of RNAV for the en route flight tests had a minimal effect on pilot workload, and to a small extent, reduced pilot workload in some areas. The need for each pilot to manually load the 12 needed waypoint and associated VOR data (for three patterns) into the NCU was eliminated by the use of a preprinted waypoint data card. During flight, the only RNAV workload required by the pilots was in changing waypoints at the proper time on the CDU and changing OBS settings for new courses associated with the waypoint changes.

There was no need for the pilot to change VOR frequencies during these flights although a different VOR/DME station was used for each of the pilot's three patterns. Since the VOR frequencies were prestored with the associated waypoint data, the auto-tune feature in the RNAV system automatically tuned the aircraft's VOR receiver to the station associated with the selected waypoint data.

FINAL APPROACH WORKLOAD. There was a slight increase in pilot workload during the final approach tests at those times when the pilot was required to also use VNAV starting on the base leg and ending at MAP (runway threshold). Flying 2D RNAV requires the pilot keep the RDI needle centered and frequently check his altimeter for altitude. Flying 3D RNAV is very similar to flying an instrument landing system (ILS) approach in that the pilot must keep the RDI lateral deviation needle centered as well as keeping the RDI glide slope bar centered when exercising VNAV. This means almost total concentration on both areas of the RDI during a VNAV phase of an RNAV flight. Pilots must apply this same kind of concentration during an ILS approach, but flying 3D RNAV, this concentration can be required in the en route, terminal, and the approach airspace.

In other portions of the final approach phase tests, there was minimal affect on pilot workload. The pilot was not required to manually load the required 30 waypoint data for the five consecutive approach patterns he flew. The first group of 20 waypoints were loaded prior to departure and the second card, consisting of 10 waypoints, was loaded during flight, after the first 10 waypoints had been flown. Figure 3 provides an example of a preprinted data card used in these tests.

There was no noticeable increase in pilot workload while executing the RNAV extended downwind leg maneuvers. The pilots did not use the RNAV parallel offset function to execute the standard extended downwind leg maneuver, as described in the scenario section, which would have required approximately

5 seconds to formulate an offset message on the CDU and activate the offset function. The offset function for the standard extended downleg maneuver was satisfactorily flown on nondata flights, but the pilots encountered some execution timing problems in following the proper sequence of events using the parallel offset function. They were allowed to use their own method for executing a standard extended downwind leg for the data flights. For this downwind execution maneuver, all pilots preferred to continue past the normal baseleg waypoint to the required number of miles (3 nmi in each case), and using turn anticipation, turned onto baseleg, selected the GATE waypoint, and used the RDI crosstrack deviation needle indication to maintain the offset course until they were ready to turn onto the final approach course.

Although four different VOR's were used during the approach patterns, the RNAV system's VOR frequency auto-tune feature eliminated the pilot workload requirement of manually changing VOR frequencies.

Minimum pilot workload was required (5 to 10 seconds) to select a desired altitude and flightpath angle for each VNAV portion of these flights.

After completing the turn to the final approach course, each pilot was required to change from the en route navigation mode to the approach mode. This was done by changing the mode switch on the CDU from one setting to the other.

Occasionally, pilots did not promptly select the approach mode due to the usual high pilot workload involved in this phase of each flight.

ROUTE A2 (SID/STAR) PILOT WORKLOAD. There was a definite increase in overall RNAV pilot workload during the A2 route flight tests. This increased workload varied depending on the flight plan scenario being used for each of the five patterns flown per pilot.

One of the objectives of these tests was to study the operational effects of RNAV in the terminal airspace. Five flight plan scenarios provided certain RNAV flight maneuvers to be executed at some point during each pattern. The pilots did not have preknowledge of which maneuvers they were to execute during each pattern. The airborne observer, acting as ATC, provided the scenario data at the proper point during each flight. These RNAV maneuvers included:

1. Parallel offset (including inside and outside parallel offset turns during waypoint changes).

2. Flying direct to an alternate waypoint for flightpath reduction.

3. Delay fans (path stretching).

4. Vertical navigation.

5. Alongtrack offsets.

6. Impromptu runway change.

Five of the six subjects had little or no prior experience in flying most of these RNAV maneuvers. Each of the five pilots were provided with 2 hours of training in the GAT-II cockpit simulator learning to fly these maneuvers using the EDO RNAV system and in formulating the proper computer messages for the execution of these maneuvers.

After these pilots had completed their training in the GAT-II, there was a 1 to 3 month delay in starting their data flights. This time gap was due to uncontrollable scheduling delays, i.e., nonavailability of aircraft, pilots, tracking radar, etc., and it did affect pilot proficiency, to varying degrees, in performing some of the required RNAV maneuvers on the A2 route. Once the A2 route data flights were ready to start, the GAT-II was not available when needed for additional training. To reduce possible proficiency problems, each pilot was given a preflight briefing that included all aspects of the maneuvers that were flown during the GAT-II training. If a pilot had a question on how to select a specific RNAV function on the CDU, he was allowed to practice this on the CDU prior to data flights.

As in the other test phases, the use of a preprinted flight plan card to automatically load the NCU slightly reduced normal pilot workload. It relieved the pilot of manually loading the waypoint data (except for three of the six pilots involved in an impromptu runway change) and the need of manually changing VOR frequencies.

Flying the A2 route in a 2D mode (without VNAV) is comparable to flying point-to-point VOR with a VOR approach to a landing. Using this type of RNAV system capability, a pilot normally experiences a slight reduction in pilot workload over conventional navigation and better navigation orientation than when radar vectored.

However, the requirements of ATC to meter and space aircraft often require deviations from a flight planned route. These deviations can affect normal pilot workload in both conventional navigation and RNAV. Using experimental 3D RNAV procedures and maneuvers in lieu of conventional navigation procedures and radar vectors produced the following effects on pilot workload.

1. Parallel Offsets With Inside and Outside Waypoint Turns—It took each pilot approximately 5 seconds to select the desired offset distance and activate offset mode on the CDU. The pilots encountered no workload problems navigating to the required parallel offset distance (similar to a vector). The pilots did experience an increase in workload during preparations for executing a parallel offset for an inside or outside waypoint turn. The waypoint alert indicator, which activates within 0.9 nmi of a waypoint, was not usable during the waypoint offset turns. Not being able to use this indicator required the pilots to monitor the distance-to-waypoint display more frequently in preparation for timing the start of the turn.

If a pilot was distracted by other duties when he reached the desired turning point position, he would overshoot the turn to the new course. Also, each pilot had to mentally calculate turn anticipation distance and add (inside) or subtract (outside) it to/from the offset distance and maintain the proper offset distance through the turn and onto the next offset route leg. A miscalculation on a pilot's start turn distance would cause an overshoot or an undershoot. Figure 14 provides an example of a waypoint turn during a parallel offset situation. Because the route legs used in these tests were relatively short in distance, the pilots could not delay their turn or make a shallow turn toward the offset course or delay their return to the parent course. If a pilot did not respond properly in executing an "inside" parallel offset of 5 nmi he would reach the offset turn point before he reached the required parallel offset distance (this was not a problem on the 4 nmi "outside" parallel offset). If a pilot did not respond properly in returning to the parent course from a parallel offset, he was likely to reach the vicinity of the waypoint in use before arriving at the parent course, which was undesirable. He could usually expect an overshoot or undershoot at that waypoint. To execute this type of parallel offset correctly required an extreme amount of pilot concentration and precision.

2. Flying Direct To an Alternate Waypoint for Flightpath--The pilots encountered no increase in normal workload when they were required to deviate from their flight planned route and fly direct from their present position to the outer final approach waypoint (HOTEL) from over waypoint VICTOR. This maneuver reduced the total flightpath distance from VICTOR to MAP-4 waypoint by approximately 4 nmi and bypassed one waypoint. This maneuver is equivalent to a pilot being rerouted from his present position direct to another VOR or to an ILS outer marker.

3. Delay Fan for Flightpath Stretching--There was no significant increase in pilot workload, in executing the delay fans in these tests. It required approximately 5 seconds to select the required parallel offset distance and activate the offset mode on the CDU. It required about 1 second to turn off the offset mode before proceeding direct to the HOTEL waypoint for runway 4 or until intercepting the extended final approach course for runway 13. An example of the path stretch maneuver for runway 13 is provided in figure 15.

4. Vertical Navigation--There was a slight increase in pilot workload during a portion of the A2 route in which VNAV was applied. All pilots were required to fly in the VNAV mode from the beginning of the STAR portion of the A2 route down to runway threshold. VNAV was optional on the SID and transition portion of this route. The pilots selected those waypoint crossing altitudes shown on the STAR and approach charts. These altitudes were modified when required in the flight plan scenarios. It required 6 to 10 seconds for the pilots to select the desired altitude and flightpath angle data on the CDU, barring keyboard errors during the selection process.

Pilot workload did increase when using the RDI glide slope bar to maintain the proper vertical flight profile in addition to maintaining the proper lateral flight profile. This required almost total concentration on both areas of the RDI and altimeter in the VNAV mode. The altimeter had to be closely monitored to anticipate "level off" so as not to ascend or descend past the selected altitude.

5. Along-track Offset--This is another form of VNAV that was applied during these test with use of scenarios. There was additional pilot workload executing these maneuvers over and above normal VNAV. This additional workload was primarily due to a more complicated procedure in selecting this function on the CDU and in trimming the aircraft for a steep descent angle called for in one of the scenarios.

This maneuver was required in three of the five patterns during the STAR portion of the A2 route. The scenarios required VNAV flightpath angles of approximately 6°, 3°, and 1.5°. Since the pilots used computer-generated flightpath angles, the angles varied depending on what point along the course that the computed angle was activated by the pilot.

Once the pilots were given the along-track data by the observer, it took 20 to 30 seconds to complete the required along-track selection and activation process on the CDU. All pilots were prone to making errors in the formulation of this along-track message on the CDU, which required additional workload and "heads down" time to correct the error. A contributing factor to these errors was that keyboard selection process was similar to the straight VNAV selection process, but the message formulation sequence on the CDU keyboard was different.

The pilots had only experienced this CDU selection process during their training in the GAT-II simulator; therefore, pilot proficiency in this area was also a contributing factor.

6. Impromptu Runway Change--The three pilots that had the three additional waypoints prestored for the impromptu change from runway 4 to runway 13 encountered little or no additional workload in making the change other than reorientating themselves to the change of runways. They only had to change the CDU waypoint selector to the desired waypoint data at the proper time. However, the three pilots that were required to manually load the three waypoint data into the NCU encountered an extremely high workload during this process. It took the first pilot 2.3 minutes to load these waypoints into the NCU and verify data accurracy. The "heads down" time was so extensive he had the safety pilot take control of the aircraft until the waypoint data was loaded. By the time he had completed the waypoint loading, it was too late to execute a delay fan as required in the scenario. It took the second pilot 2.9 minutes to complete and verify the manual waypoint loading. He was able to do his own navigation and execute the delay fan afterward without assistance from the safety pilot. It took the third pilot 2.9 minutes to complete and verify the manual waypoint loading. Due to extensive "heads-down" during this time, he had the safety pilot take control of the aircraft, but he was able to execute the delay fan afterward.

PILOT BLUNDERS AND ERRORS.

Each time a pilot error evolved into a situation that would have caused a disruption of aircraft traffic flow (in a true ATC environment), placed the aircraft into a possible hazardous flight situation, or strayed outside protected airspace, it was recorded as a blunder. The pilot was given time to detect a potential blunder and take corrective action. The safety pilot or the airborne observer intervened only to prevent a hazardous situation and to prevent the flight from being aborted before completion. Pilot errors were observed, but not always recorded on the observer log. These errors did not cause a detrimental effect to the flight because they were minor or quickly detected and corrected. During the tests that specifically dealt with the en route and final approach areas, no pilot blunders or errors occurred. This was primarily due to simplified flight patterns that required minimal RNAV pilot workload and minimal use of the RNAV system's operational capabilities, i.e., automatic waypoint data loading, waypoint selector switch, and VNAV selections. However, pilot blunders and errors did occur during the A2 route flights. These occurrences were mostly due to the kinds of flight maneuvers required in the A2 route flight tests, which in turn, required full use of the RNAV system's operations capabilities.

PILOT BLUNDER RESULTS. A total of 11 blunders were recorded during the 30 A2 route flights. These blunders fell into four categories:

1. Overshoots at waypoint turns that carried the aircraft outside of protected airspace.

2. Selection of wrong waypoints during along-track offset maneuvers.

3. Pilot workload due to manual loading of waypoint data.

4. Pilot inattention to RDI crosstrack indications.

Within these categories the blunders were quantified as follows:

a. There were five blunders (55 percent of total blunders) in which the aircraft strayed outside the 2 nmi protected en route airspace while the pilot was turning to the new course. One overshoot blunder occurred on the turn at TANGO waypoint while the pilot was on a 4-nmi left parallel offset (outside parallel offset turn). The aircraft strayed approximately 3 nmi beyond the offset turn point.

Three overshoot blunders occurred at UNIFORM waypoint during the turn to a new course. One pilot was attempting to return to the parent course from a 4-nmi left parallel offset and overshot the turn at UNIFORM waypoint. This pilot had an overshoot blunder at the previous waypoint (TANGO) while on an "outside" parallel offset turn. (The blunder at TANGO very likely contributed to the blunder at UNIFORM.)

One overshoot blunder occurred at VICTOR waypoint. This blunder occurred while the pilot was "heads down" selecting an along track offset on the CDU when waypoint passage at VICTOR occurred. He recovered too late to make the turn before straying outside of the 2-nmi protected airspace.

b. There were two blunders (20 percent of total blunders) in which both pilots selected the next waypoint too soon during an along track offset maneuver.

This early selection of the next waypoint caused the computed flightpath angle to be cancelled out of the NCU and vertical navigation was lost. Both pilots did not attempt to select a new flightpath angle. If they had done so, and continued vertical navigation, these two blunders would have been defined as pilot errors.

One of the blunders occurred while the pilot was on an along-track offset that would take the pilot 4 nmi past VICTOR waypoint before the aircraft reached the required altitude. Instead of using VICTOR waypoint until the aircraft was at the desired distance and altitude beyond this waypoint, he selected the next waypoint (GOLF) and lost vertical navigation.

The other blunder occurred during an along-track offset to GOLF waypoint. The pilot inadvertently selected HOTEL waypoint during this offset maneuver and lost vertical navigation. He discovered his error and reselected GOLF waypoint, but he did not reselect a new flightpath angle which is necessary to reactivate vertical navigation.

c. There were two blunders (20 percent of total blunders) in which three of the six pilots were required to manually load three waypoints into the NCU as the results of an impromptu runway change. Two pilots were not able to navigate the aircraft during this manual waypoint loading. The safety pilot was required to take over navigation during this time, and the two subject pilots completed this waypoint loading too late to execute a delay fan maneuver to the final approach course. These two blunders were considered borderline cases as to whether pilot and RNAV system capability had been exceeded in attempting manual waypoint data loading under the specified conditions, or whether they were actual pilot blunders. It requires two pilots to fly the Gulfstream 159 properly, but one of the two pilots was able to manually load the three waypoint data and still perform his own navigation. He was, also, able to execute the delay fan afterward without navigation assistance from the safety pilot. All three pilots had similar pilot experience prior to these safety flights. After serious consideration, it was determined that these two cases be defined as blunders.

d. Due to inattention of increasing RDI crosstrack error, one pilot drifted outside the 2-nmi airspace in the vicinity of SIERRA waypoint.

PILOT ERROR RESULTS. Except for one OBS setting error made during the A2 route flights, all other pilot errors occurred during the formulation process of selecting various RNAV operational functions on the CDU. A count was not kept of these errors, and the pilots corrected them before they could evolve into a blunder situation. However, correcting these error increased pilot workload and "heads down" time.

The most frequent pilot errors, using the CDU, occurred during the formulation process for the selection of along track offsets. (Lack of experience in the message formatting sequence was a contributing factor.)

Only an occasional error was made while selecting a parallel offset or while manually formulating waypoint data. No errors were noted during the selection of VNAV profiles.

One OBS setting error occurred when the pilot selected an OBS course of 120° instead 121° for navigation to HOTEL waypoint. Although the pilot did not correct this error, it had minimal effect on navigation accuracy to HOTEL.

RESULTS OF REQUIRED OPERATIONAL MANEUVERS.

Each pilot was required to execute certain operational maneuvers to satify test requirements. While they knew what was required, they were not forewarned of when or on which particular pattern these maneuvers would be required. The airborne observer provided this information from a list or scenario at the proper time for each particular pattern. The recommended method of executing these maneuvers are described in the SCENARIO section. Most of the problems that occurred executing these maneuvers are described in the PILOT WORKLOAD section. There were no operational maneuver requirements for the en route tests other than flying the flight planned route.

PARALLEL OFFSETS. Each of the six pilots was required to execute two parallel offsets during the A2 route tests. On one pattern, they flew a 5-nmi right parallel offset that required them to make a waypoint turn (inside) and still maintain the required offset distance during the turn and onto the new offset course. This parallel offset instruction was given at the SIERRA waypoint and was cancelled at the 10 nmi DTW UNIFORM.

On another A2 route pattern, the pilots flew a 4-nmi left parallel offset that required them to make a waypoint turn (outside) and still maintain the required offset distance during the turn onto the new offset course. This parallel offset instruction was given at the SIERRA waypoint and was cancelled at the 10 nmi DTW UNIFORM. Figure 14 provides an example of an actual left parallel offset track.

Figure 36 shows the combined graphic results of a 4-nmi left offset around the turn at waypoint TANGO. The steady-state offset statistics for this maneuver are presented in table 20. The plot and the statistics clearly show that the pilots were able to fly this outside offset about as well as the parent course. The turn performance was consistent (overshoot tendency) but somewhat less than desirable with one blunder occuring, and with one other situation which was very close to being a violation of airspace requirements. Figure 37 graphically illustrates the results of the 5-nmi right offset inside the turn at TANGO. The statistics for the steady-state offset legs are presented in table 21. The plot and the statistics show the difficulty the pilots encountered on this inside offset. Turn performance was highly inconsistent and the pilots never really established the second leg of the offset once the turn was completed.

In the case of the outside offset, the inherent lengthening of the offset legs was beneficial to offset performance, while in the case of the inside offset,

TABLE 20. FOUR-NMI LEFT (OUTSIDE) OFFSET STATISTICS

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
SNCT	541	0.153	0.213
CPCT	541	-0.030	0.133
FTE	544	-0.274	0.343
OBSN	544	-0.120	0.083
TSCT	541	-0.354	0.281

TABLE 21. FIVE-NMI RIGHT (INSIDE) OFFSET STATISTICS

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
SNCT	186	-0.014	0.099
CPCT	186	-0.080	0.092
FTE	186	0.041	0.775
OBSN	186	-0.152	0.056
TSCT	186	-0.308	0.746

TABLE 22. DIRECT TO HOTEL STEADY-STATE STATISTICS

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
SNCT	1,016	-0.078	0.596
CPCT	1,016	0.234	0.554
FTE	932	-0.122	0.630
OBSN	932	-1.106	0.600
TSCT	932	-0.990	0.726

the inherent shortening of the offset legs was highly detrimental to offset performance. In both cases, the moving of the turning point evidently caused problems for completing the turn in a satisfactory manner.

DIRECT TO WAYPOINT. Each of the six pilots was required to bypass a flight planned waypoint during one A2 route pattern and fly direct to another waypoint on the route to shorten the aircraft's flightpath to the final approach course (HOTEL). Instead of flying the normal waypoint sequence of VICTOR to GOLF to HOTEL (outer waypoint for the final RNAV approach to runway 4), each pilot was instructed, at VICTOR, to proceed direct to HOTEL for an RNAV approach to runway 4. This maneuver bypassed GOLF waypoint.

Figure 38 shows the turn performance at waypoint VICTOR when the direct route to waypoint HOTEL was employed. The parent course about the turn represents the ideal straight-line course from VICTOR to HOTEL. The plot shows that allowing the pilots to formulate their own course to HOTEL created a wide variety of unpredictable results for the turn at VICTOR. The statistics listed in table 22 show that the pilots could fly direct to HOTEL with satisfactory performance once the new course was established. However, it could not be expected that they would remain within the ±2-nmi width about the ideal course, because the "seat of the pants" OBS course induced a mean bias error of about 1-nmi in TSCT.

DELAY FAN. Each of the six pilots was required to execute two delay fan (path stretching) maneuvers during the A2 tests. On one pattern, the delay fan was executed while on the base leg course to runway 4. The pilot was instructed to start a 3-nmi right offset at the 10 nmi DTW HOTEL. Upon reaching the 3-nmi offset, the pilot was instructed to proceed direct to HOTEL for an RNAV approach. All six pilots completed this maneuver satisfactorily.

On another route A2 pattern, each of the six pilots was required to execute a delay fan maneuver while on the base leg course to runway 13. At the 10 nmi DTW BALTIC, the pilot was instructed to make a 3-nmi left parallel offset and maintain the offset until reaching the extended final approach course for runway 13. Only three pilots completed this type delay fan. Two of the pilots had to manually load 3 waypoints into the NCU (impromptu runway change) for the RNAV approach to runway 13 and did not complete this process in time to execute the delay fan. On the other incompleted delay fan, the preloaded waypoint data for GOLF and BALTIC became "garbled" in the NCU (cause unknown) and had to be manually reloaded into the NCU. By the time this reloading was complete, it was too late to execute the delay fan. Figure 15 provides an example of an actual delay fan track to runway 13. Figure 39 shows the combined performance for the delay fan on the base leg to runway 4. Figure 40 shows the combined performance for the 3-nmi left parallel offset on the base leg to runway 13.

VNAV AND ALONG-TRACK OFFSET. VNAV profiles were flown in both the final approach and route A2 test phases. Along-track offsets, which are a variation of VNAV, were required during the STAR portion of the A2 route flights. All six subject pilots applied the recommended VNAV and along-track offset maneuver procedures described in the SCENARIO section.

Each of the four pilots in final approach tests flew five VNAV patterns starting at base waypoint for runways 4 or 13 and ending at the MAP waypoint. During the route A2 tests, each of the six pilots flew five VNAV patterns starting at the first STAR waypoint (UNIFORM) and ending at the MAP waypoint for runways 4 and 13 at NAFEC. Intergrated with A2 route VNAV maneuvers were three patterns in which along-track offset maneuvers were required by each of the six pilots. These offsets were designed to provide computed flightpath angles of approximately 6°, 3°, and 1.5°. The resultant angle varied depending on how soon the along-track offset was activated after the instruction was given. On the 6° offset, each pilot was instructed to maintain 9,500 ft m.s.l. until passing VICTOR and then descend so as to reach 3,500 ft m.s.l. at 5 nmi DTW GOLF during the descent. On the 3° offset, each pilot was instructed to cross UNIFORM at 10,500 ft m.s.l., then descend so as to reach 6,500 ft m.s.l. at 2 nmi DTW VICTOR and maintain 6,500 ft m.s.l. until passing VICTOR. On the 1.5° offset, each pilot was instructed to descend to 9,500 ft m.s.l. after passing UNIFORM. At the 10 nmi DTW VICTOR, each pilot was instructed to descend so as to reach 6,500 ft m.s.l. at 4 nmi past VICTOR BEFORE CONTINUING DESCENT.

All final approaches to runways 4 and 13 resulted in a computed flightpath angle of approximately 3° during the last 5 nmi of the final approach course to the MAP waypoint down to an altitude of 150 ft m.s.l. at MAP.

<u>IMPROMPTU RUNWAY CHANGE</u>. Each of the six pilots was required to execute an impromptu change of runways (from runway 4 to runway 13) during one of the route A2 tests. Three pilots were allowed to prestore the new assigned runway waypoint data (3 waypoints) prior to takeoff. The remaining three pilots were required to manually load the new assigned runway waypoint data into the NCU. At no later than 5 nmi DTW GOLF waypoint, each pilot was advised of a change in the landing runway and recleared for an RNAV arrival to runway 13 via direct GOLF, direct BALTIC, cross BALTIC at 3,200 ft m.s.l. or above. Figure 14 provides an example of the standard approach track to runway 4 from GOLF (G) and figure 15 provides an example change track to runway 13 from GOLF (G), including a delay fan.

<u>EXTENDED DOWNWIND LEG</u>. Each of the four pilots was required to execute 2 extended downwind legs during the final approach tests; one with a standard base leg (figure 9), and one with a modified base leg (figure 10).

When the aircraft was approximately 5 nmi DTW BASE waypoint for either runway 4 or runway 13, each pilot was instructed to extend the downwind leg 3 nmi before turning onto the base leg (standard extended downwind leg), cleared for an RNAV approach upon reaching the extended final course. For the modified extended downwind leg, each pilot was instructed to extend his downwind leg 3 nmi and then proceed direct to GATE, cleared for an RNAV approach. An example of both extended downwind leg tracks are provided for in figure 16.

The pilots used their own methods for executing the standard extended downwind leg. Each pilot slightly overshot the final approach course. No problems occurred in executing the modified extension.

TURN ANTICIPATION.

Each of the six subject pilots was required to use some form of turn anticipation for every waypoint course change. The application of turn anticipation by leading a turn at 1 nmi per 100 knots TAS, as defined in AC 90-45A, was recommended to these pilots prior to start of flight testing. However, the AC 90-45A application was not mandatory, and each pilot elected to use his own method of applying turn anticipation.

Two methods of turn anticipation were used in these flight tests.

1. One method used by three pilots was to select the new waypoint and change the OBS to the new course shortly after the waypoint alert light started flashing (0.9 minutes either side of the waypoint in use), but they continued to fly their present compass course. This caused the RDI needle to display a crosstrack deviation from the new OBS course. As the crosstrack deviation decreased, each pilot used his own judgment in anticipating the point of when to start turning to the new OBS course.

2. The method used by the other three pilots was to estimate the turn anticipation point based on the DTW readouts to start the waypoint turn. As the turn was started, they would then reset the OBS to the new course and select the new waypoint. This method was used by all pilots for turn anticipation during parallel offset maneuvers where waypoint turns to a new course was required.

To analyze the turn anticipation performance of the pilots on the A2 route, the tracking radar data for each pilot was plotted to make a composite plot of all pilots for each turn. The desired course (as well as a ±2-nmi route width) was also plotted on the composite. The analysis of turn performance follows.

ROMEO 88° TURN ANGLE. Turn performance at ROMEO (figure 41) was quite good. All pilots turned inside the waypoint, except for one instance when a pilot wandered slightly and overshot the turn. Including this instance, all were well within the ±2-nmi route width.

SIERRA 13° TURN ANGLE. Turn performance at SIERRA (figure 42) was adequate. However, one pilot did deviate outside the ±2-nmi route width as shown in the plot. Investigation revealed that in this instance the mean FTE was about 0.74 nmi left between ROMEO and SIERRA, and about 1.46 nmi left between SIERRA and TANGO.

TANGO 76° TURN ANGLE. Turn performance at TANGO (figure 43) was quite good, and rather consistent. On one occasion, however, a pilot almost traveled outside the ±2-nmi route width. Investigation showed that the mean FTE approaching TANGO for this instance was 1.21 nmi left of the course.

UNIFORM 97° TURN ANGLE. Figure 44 shows the combined turn performance at UNIFORM for scenarios 1, 4, and 5. Figure 45 shows the combined turn performance at UNIFORM for scenario 2, while figure 46 shows the combined turn performance at UNIFORM for scenario 3. Turn performance at UNIFORM was poor. There was a consistent severe overshoot tendency for which the statistics offered no apparent explanation. The pilots simply did not begin to turn soon enough. This was quite evident when they were returning from the inside parallel offset at TANGO on scenario 2. For scenario 3, which included the outside parallel offset at TANGO, the performance was about the same as without the offset. The poor turn anticipation caused three violations of the $\pm$2-nmi route width (3 blunders).

VICTOR 52° TURN ANGLE. Turn performance at VICTOR (figure 47) was reasonable, even though statistics showed that guidance signals were poor in this area (0.892 nmi one standard deviation for SNCT between VICTOR and GOLF). One pilot wandered outside the $\pm$2-nmi course width when a data entry operation distracted him.

GOLF - RUNWAY 4 52° TURN ANGLE. Turn performance at GOLF (figure 48) for a runway 4 approach was adequate, with no blunders occurring.

GOLF - RUNWAY 13 21° TURN ANGLE. Turn performance at GOLF (figure 49) for scenario 5 was sloppy. Statistics showed that guidance signals were erratic in the area (0.726 nmi one standard deviation for SNCT between GOLF and BALTIC). This was also a high work load area (impromptu runway change to runway 13).

HOTEL 83° TURN ANGLE. Turn performance at HOTEL (figure 50) approaching from GOLF was reasonable. Most pilots turned inside the waypoint. The left bias in the area of the turn was primarily due to a mean error of 0.262 nmi for SNCT.

HOTEL 55° TURN ANGLE. Figure 51 shows the turn performance at HOTEL for scenario 2 approaching direct from VICTOR. All pilots turned well inside the waypoint, but none violated the $\pm$2-nmi route width. It must be remembered that the pilots in this instance were navigating to HOTEL on an impromptu OBS course, and not the actual course from VICTOR to HOTEL. Also, SNCT had a 0.262-nmi mean error to the left of the final approach leg.

FINAL APPROACH PERFORMANCE.

Final approaches were made to runways 4 and 13 at NAFEC using four different ground stations, ACY, SIE, Milville (MIV) and Coyle (CYN). Radar tracking data for each configuration (i.e., runway and ground station) were plotted for the final approach segments from GATE to MAP. These are presented in figures 52 through 59. A $\pm$1-nmi route width is also plotted to provide a reference. Each plot also contains the tangent point distance and along track distance to MAP for the particular configuration represented by that plot. These values were estimated from the Washington Sectional Aeronautical Chart. An analysis of these approaches follows.

ACY. For both runways, the final approaches using ACY were slightly left of the final approach course. Investigation showed that in both cases there was a sensor crosstrack mean error of about 0.2-nmi left of course, which explained the deviation.

SIE. Performance using SIE was varied. Approaching runway 13, there was a left SNCT bias. However, one of the pilots overshot the course to the extent that FTE caused his approach to be mostly to the right of the desired course. Approaching runway 4, there was a mean SNCT error of about 0.2-nmi to the right. However, one pilot overshot the final course and crossed through the course twice more before stabilizing to the right.

MIV. Approaching runway 13 using MIV there was a bowing to the right of the course which resulted from a mean SNCT error of about 0.12-nmi. The further deviation to the right resulted from a higher mean for FTE. The approaches to runway 4 using MIV were very good once the pilots stabilized on the final approach course.

CYN. The final approaches to runway 13 using CYN were excellent, once the pilots converged to the desired course. The approaches to runway 4, however, were the worst flown. SNCT mean error for this configuration was about 0.76-nmi left of the final course.

SUMMARY OF RESULTS

1. The measured one standard deviation for TSCT error in the en route area was 1.391 nmi. The measured one standard deviation for TSCT error in the terminal area was 0.459 nmi. The measured one standard deviation for TSCT error in the approach area was 0.251 nmi.

2. The computed one standard deviation for TSCT error in the en route area was 1.775 nmi. The computed one standard deviation for TSCT error in the terminal area was 0.784 nmi. The computed one standard deviation for TSCT error in the approach area was 0.326 nmi. These values were computed by applying the root sum square method to individual error component statistics which were derived from paired data.

3. One standard deviation for RNAV computer crosstrack error (CPCT) and RNAV computer along-track (CPAT) error was:

AREA	CPCT (nmi)	CPAT (nmi)
Approach	0.147	0.213
Terminal	0.366	0.277
En Route	0.826	0.823

These values are for VOR/DME navigation.

4. For the approach area statistics, TSCT error had good correlation with both FTE and SNCT error, and low correlation with OBS error and RNAV CPCT error.

For the terminal area statistics, TSCT error had significant correlation with FTE, and virtually no correlation with OBS error, SNCT error, and RNAV CPCT error. For the en route area statistics, TSCT had good correlation with SNCT error, low correlation with both OBS error and FTE, and virtually no correlation with RNAV CPCT error.

5. RNAV CPCT error had significant correlation with SNCT error in all three flight areas. In each flight area, this was a negative correlation.

6. The one standard deviation for FTE in the approach area was 0.189 nmi. The one standard deviation for FTE in the terminal area was 0.544 nmi. The one standard deviation for FTE in the en route area was 0.671 nmi.

7. The error components of TSCT error identified in their order of contribution to total system error for both the approach area and the terminal area are: FTE, VOR/DME SNCT error, RNAV CPCT error, and OBS error. For the en route area, the order of contribution to total system error became VOR/DME SNCT error, FTE, RNAV CPCT error, and OBS error.

8. The largest OBS angular error, one standard deviation, was measured in the terminal area. This value was 1.219°. The largest OBS crosstrack error one standard deviation was measured in the en route area which was 0.400 nmi.

9. The pilots encountered varying degrees of difficulty in determining the point to start a waypoint turn during a parallel offset maneuver. The waypoint alert indicator was not usable to alert the pilots of a pending course change in this situation. The pilots had to rely on the distance-to-waypoint indicator and their mental calculations to determine the turn point to accurately maintain the required offset distance through the turn.

10. The modified extended downwind leg maneuver was simple for the pilots to execute. The method that the pilots chose to execute the standard extended downwind leg maneuver was, also, simple for the pilots to fly, but each pilot overshot the final approach course during the turn.

11. The capability to automatically preload flight plan waypoint data quickly and accurately into the RNAV computer minimized pilot RNAV workload.

12. The manual computer loading of waypoint data, i.e., bearing distance, VOR frequency, and VOR station altitude, caused excessive pilot workload to the three pilots assigned to this task. It took 2.3, 2.9, and 2.9 minutes, respectively, for these pilots to manually load three-waypoint data during an impromptu change.

13. Of the 11 blunders that occurred during the A2 route tests, six (55 percent of total blunders) were caused by pilots straying outside of the established 2-nmi protected airspace either side of the desired course.

14. When applying procedural turn anticipation, pilots who overshot the next course were in greater danger of violating airspace requirements. When parallel offsets about turns were employed, pilots encountered difficulty in completing a satisfactory turn maneuver. This was most evident on an inside parallel offset.

15. One standard deviation for sensor crosstrack error (SNCT) and sensor along-track error (SNAT) was:

AREA	SNCT (nmi)	SNAT (nmi)
Approach	0.228	0.197
Terminal	0.456	0.377
En Route	1.375	0.919

These values are for combined airborne sensor and ground system error.

16. For final approaches, a VOR/DME ground station located at the terminal to which the approaches were made provided better guidance than a ground station not located at the terminal.

CONCLUSIONS

1. The accuracy of VOR/DME navigation and manual flight control in the terminal area were sufficient to allow operation within the ±1.5-nmi route width on a 2-sigma basis. This applies only to the established straight-line portion of the pattern flown.

2. The use of a digital OBS indicator (selectable to the nearest degree) minimized OBS setting blunders and errors as occurred during other RNAV flight tests (see report FAA-RD-77-43).

3. The feasibility of achieving a ±1.0-nmi FTE in the terminal area was demonstrated for manual controlled flights.

4. The subjects executed the parallel offset maneuvers in a satisfactory manner with the use of a built-in offset capability. However, some of the subjects encountered problems in executing a waypoint turn to a new course while in the offset mode. Since the subjects had no indicator other than the DTW readout to alert them that they were near the offset turnpoint, they had to rely on their own judgment as to when to turn to the new offset course.

5. The subjects executed the direct to an alternate waypoint maneuver in a satisfactory manner, including the direct-to-waypoint procedure used to execute a modified extended downwind leg.

6. The subjects executed the delay fan maneuver in a satisfactory manner, except in two situations. These two subjects became involved in a blunder situation during an impromptu runway change and did not recover in time to execute the delay fan to the new runway.

7. The impromptu runway change was executed in a satisfactory manner by four of the six subjects. Two of these subjects became involved in a blunder situation while manually loading the three new waypoints into the computer. The predominate factor that caused these blunders was excessive pilot workload.

8. The subjects executed the standard extended downwind leg in a satisfactory manner until they turned on the final approach course. At that point, each pilot overshot the final approach course. This method of executing a standard extended downwind leg makes it difficult to apply turn anticipation precedures. It, also, limits the pilot's extended downwind leg to no more than 4 nmi when using the RDI to offset his base leg.

9. The capability of automatically preloading multiple waypoint flight plan data into the RNAV computer is a definite asset. It minimized pilot workload and pilot distractions from other flight duties.

10. The manual formulation and loading of waypoint data into the RNAV computer during flight causes a definite increase in pilot workload and distracts the pilot from performing other flight duties. The longer it takes to manually load this data, the more likely it is that pilot blunders and errors will occur, especially when heavy workload conditions exist.

11. The most significant factors that contributed to pilot blunders were the lack of adequate turn anticipation procedures and pilot workload.

12. The subjects' ability to use turn anticipation procedures (subjects used their own methods) varied with each subject and each turn situation. All subjects experienced difficulty of varying degrees when required to apply turn anticipation procedures during the parallel offset turns. It was difficult to judge the point at which to start the turn.

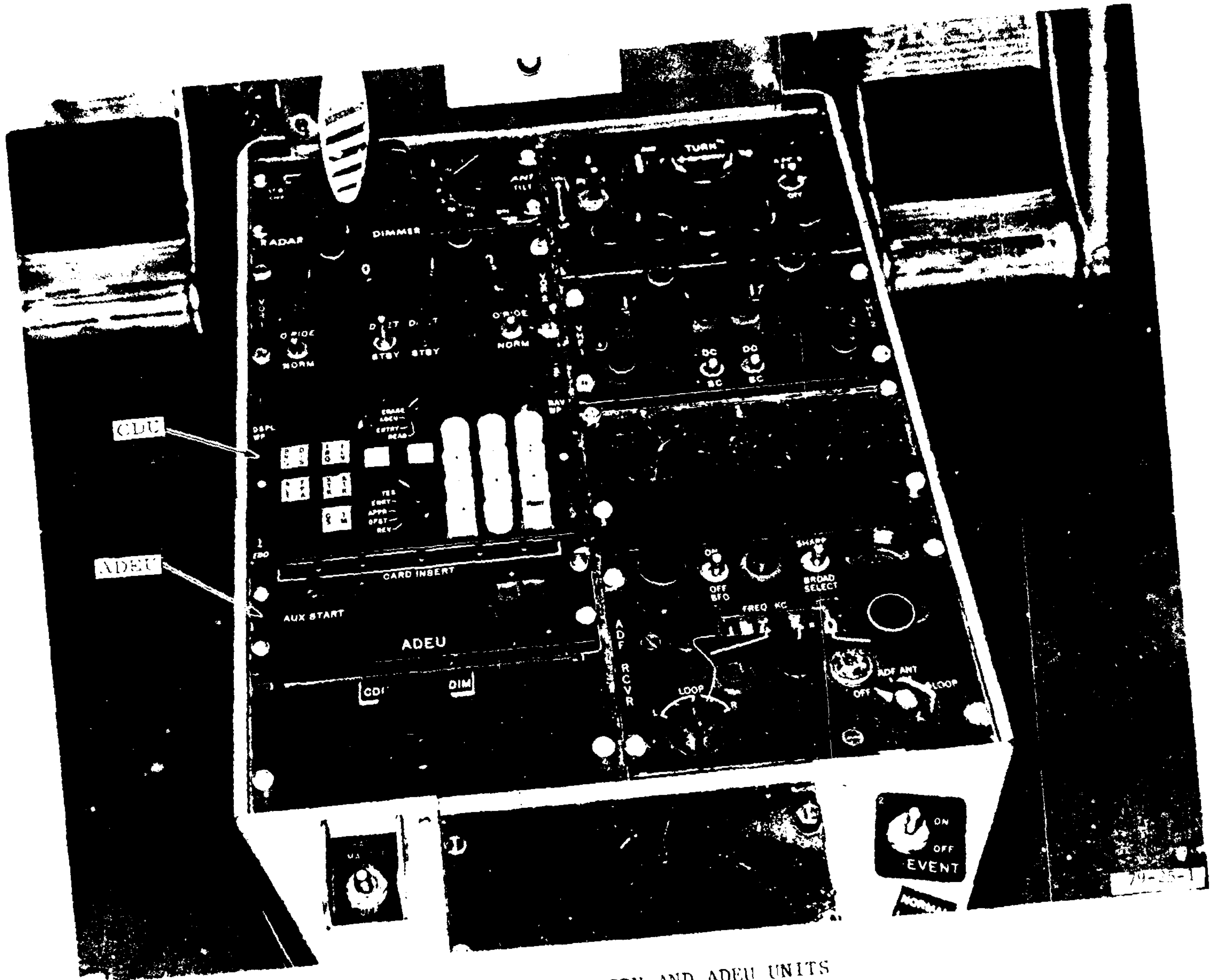


FIGURE 1. CDU AND ADEU UNITS

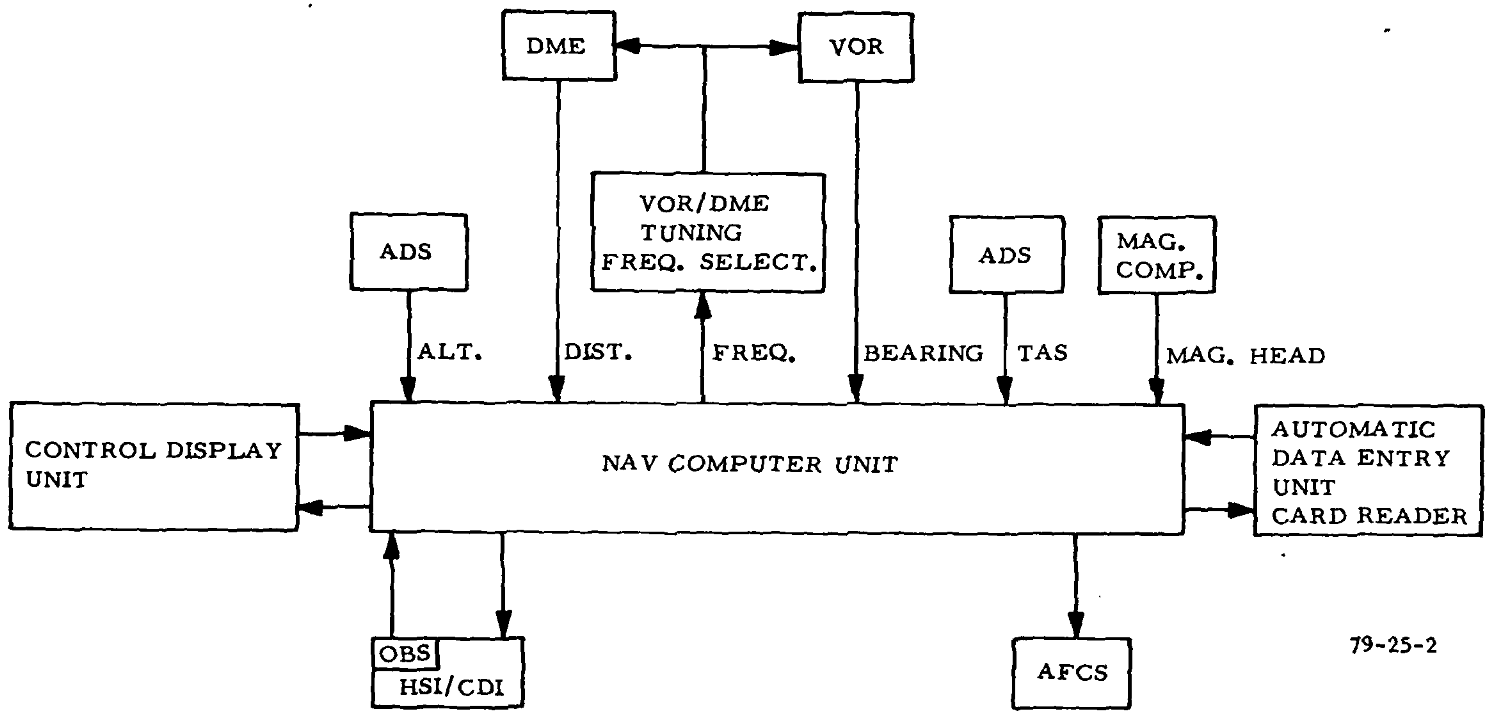
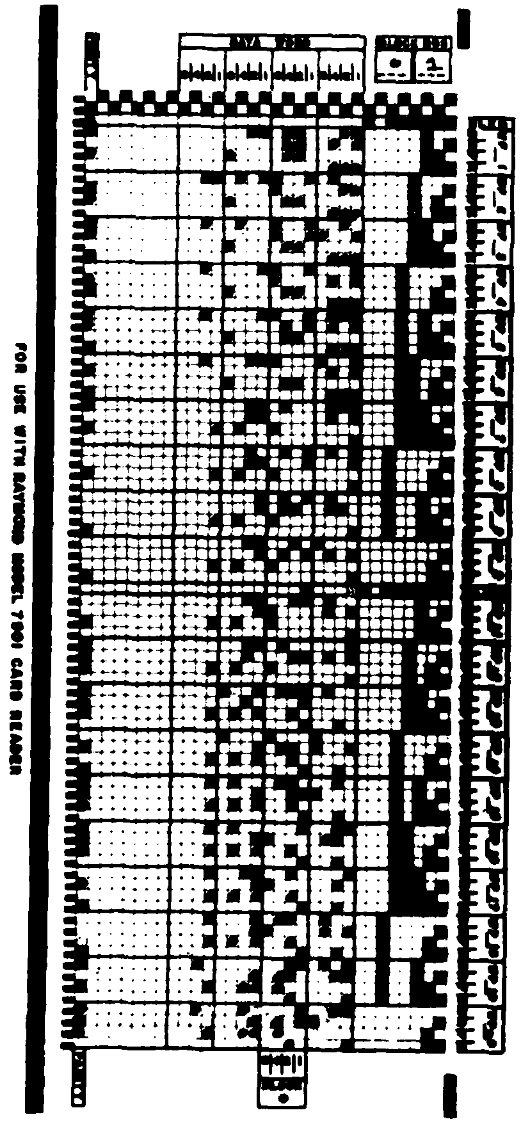


FIGURE 2. EDO RNAV SIGNAL PATH



FLT PLAN # 1

ROUTE # APPROACHES TO RWY 4.

FROM ACY

TO ACY

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	ALT	FPA	D[illegible]
1	36.3	6.5	108.6	70	ACY	NE	38	30	5	6
2	359.4	8.3	108.6	70	ACY	NW	308	30		5
3	249.2	9.9	108.6	70	ACY	BASE	218	30		15
4	219.1	8.5	108.6	70	ACY	GATE	128	26		5
5	219.7	5.5	108.6	70	ACY	FFX	38	16	3	3
6	238.9	.5	108.6	70	ACY	MAP-4	38	15	3	5
7	34.7	30.9	114.8	10	SIE	NE	38	30	5	6
8	25.5	31.1	114.8	10	SIE	NW	308	30		5
9	15.4	16.6	114.8	10	SIE	BASE	218	30		15
10	32.8	15.5	114.8	10	SIE	GATE	128	26		5
11	33.4	18.5	114.8	10	SIE	FFX	38	16	3	3
12	34.1	23.5	114.8	10	SIE	MAP-4	38	10	3	5
13	97.4	21	115.2	120	MIV	NE	38	30	5	6
14	88.8	16.9	115.2	120	MIV	NW	308	30		5
15	146.2	13.8	115.2	120	MIV	BASE	218	30		15
16	141.3	18.6	115.2	120	MIV	GATE	128	16		5
17	132.1	18.2	115.2	120	MIV	FFX	38	16	3	3
18	116.4	18.5	115.2	120	MIV	MAP-4	38		3	5
19	203.5	16.3	113.4	210	CYN	NE	38	30	5	6
20	318.4	10.4	113.4	210	CYN	NW	308			5

EFFECTIVE DATES

FROM

TO

79-25-3

FIGURE 3. PREPRINTED RNAV DATA CARD FOR ADEU

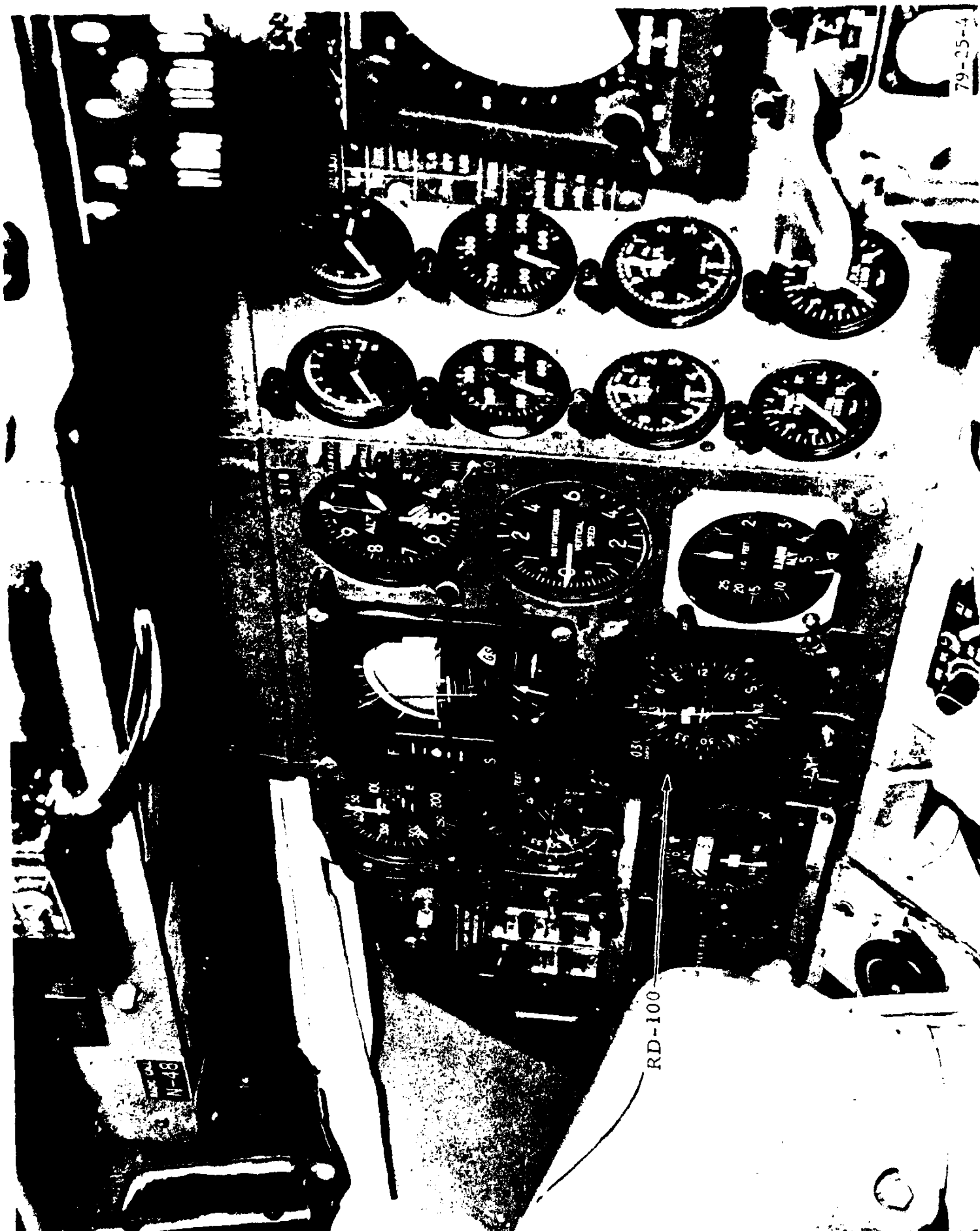


FIGURE 4. SPERRY RD-100 RADIO DIRECTION INDICATOR

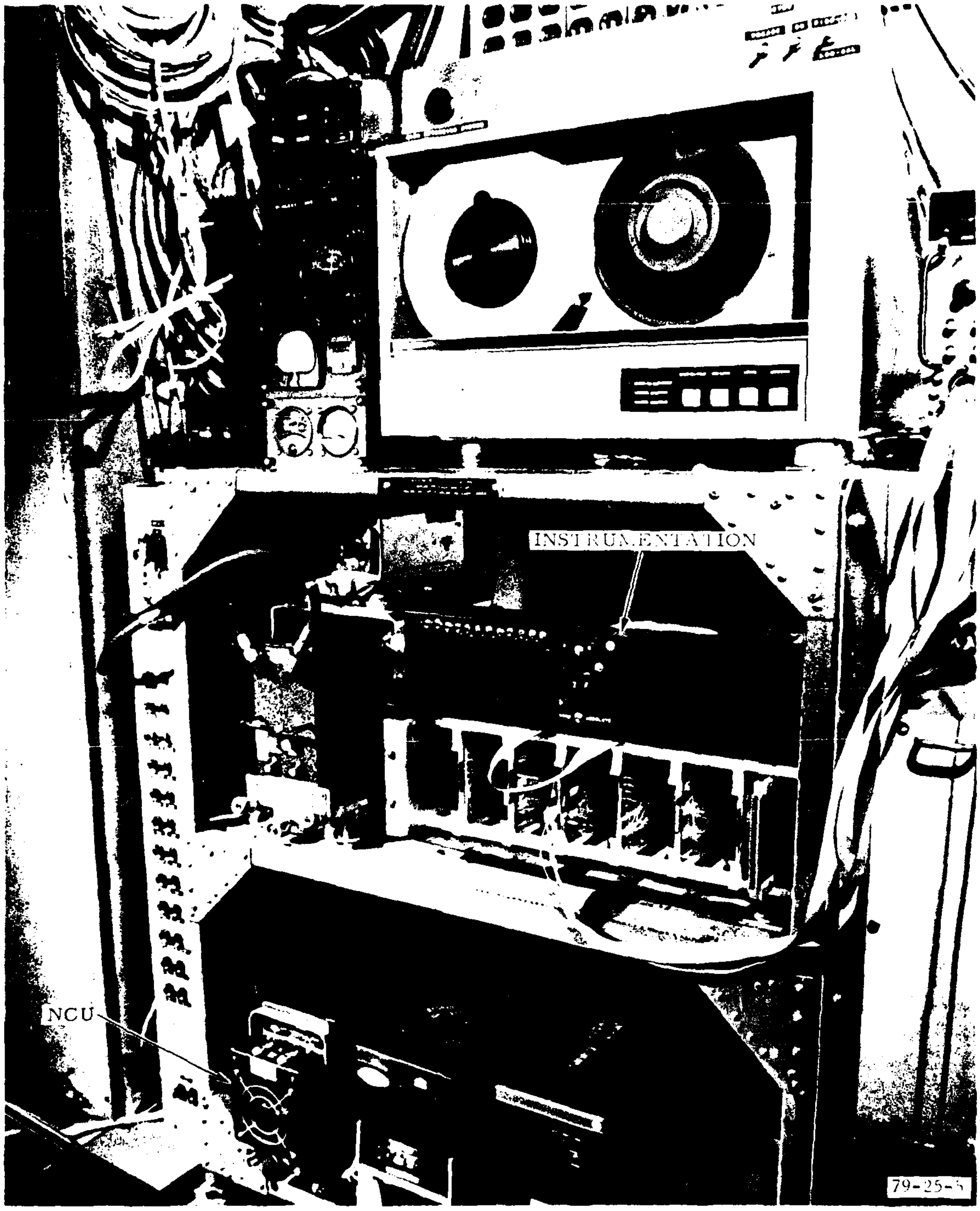


FIGURE 5. RNAV NCU AND INSTRUMENTATION SYSTEM

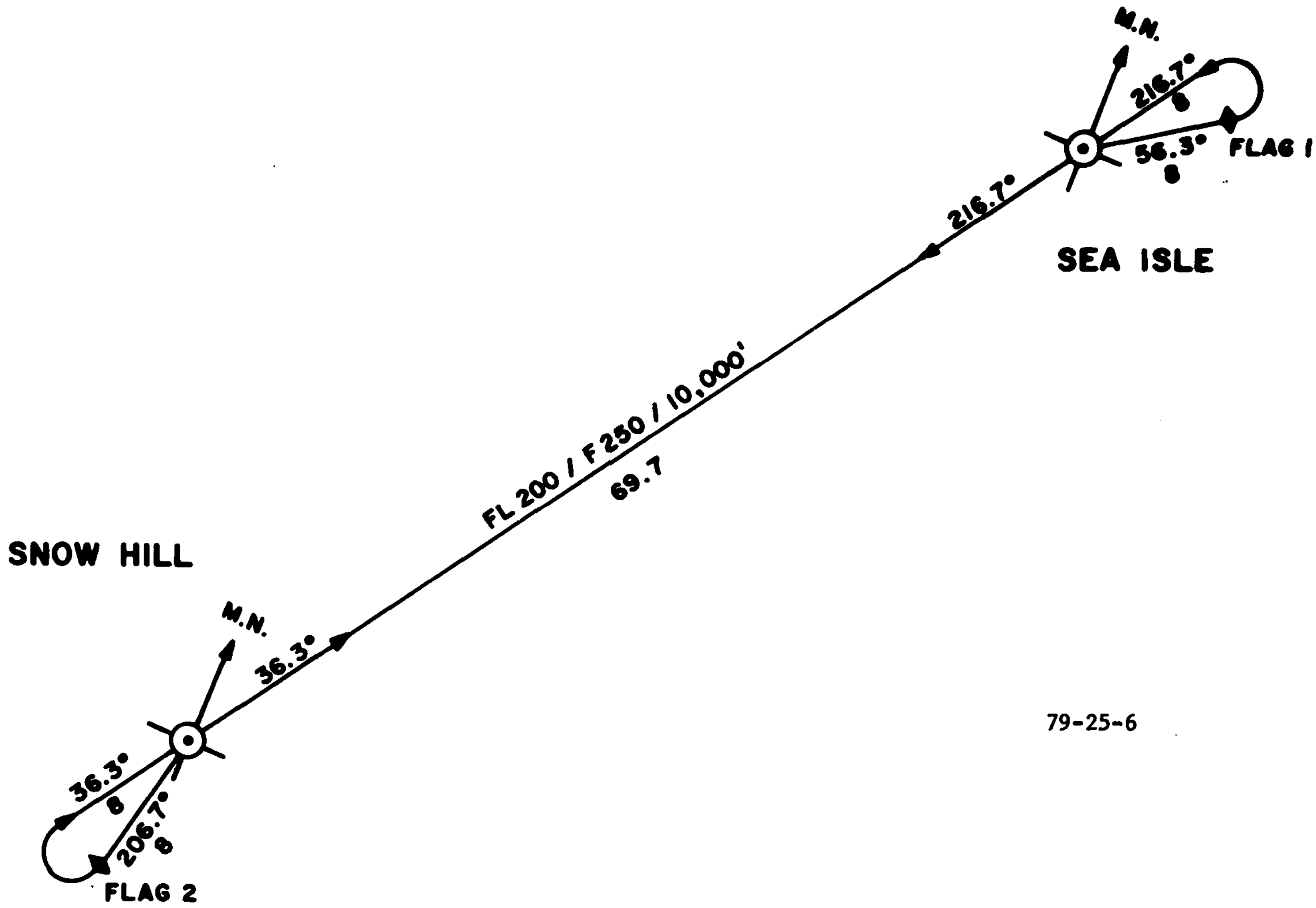


FIGURE 6. EN ROUTE FLIGHT PATTERN

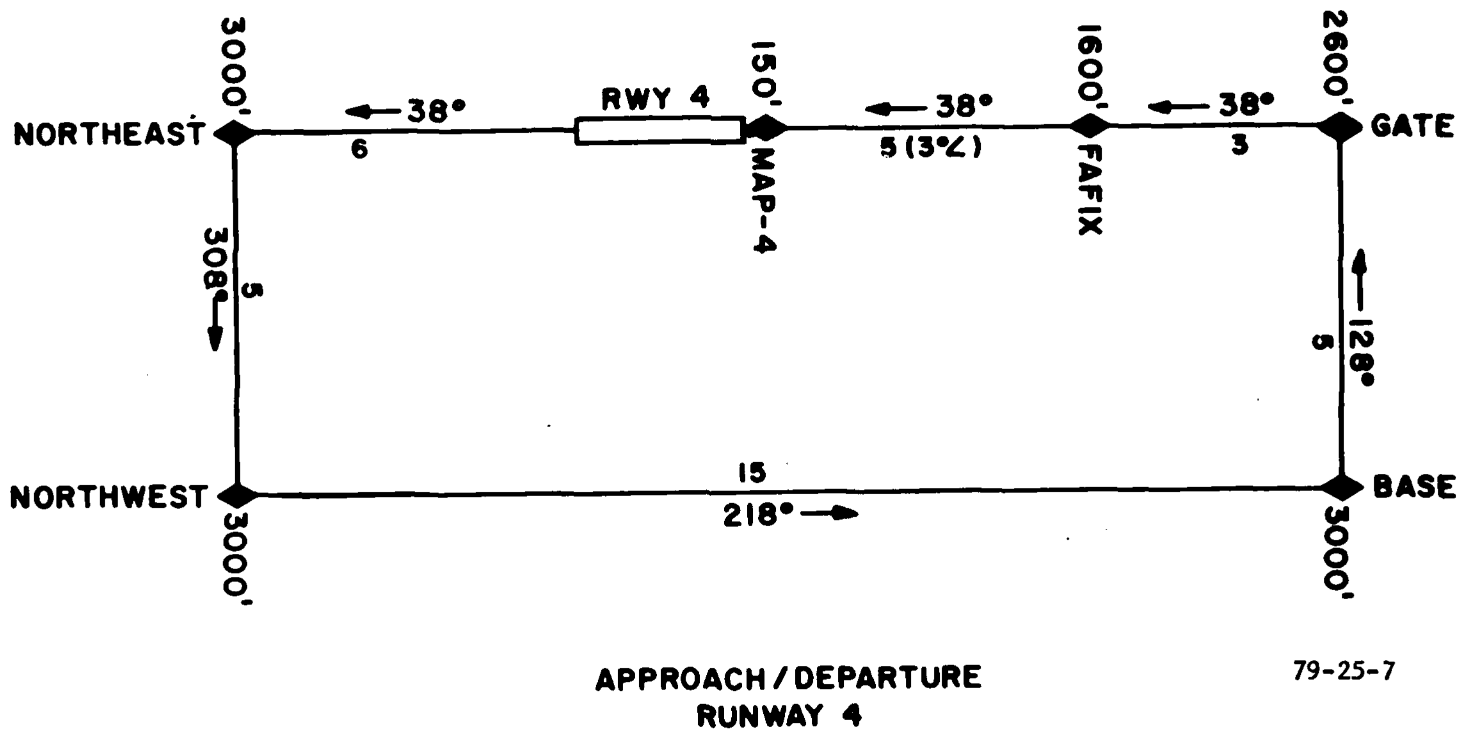


FIGURE 7. APPROACH/DEPARTURE PATTERN RUNWAY 4

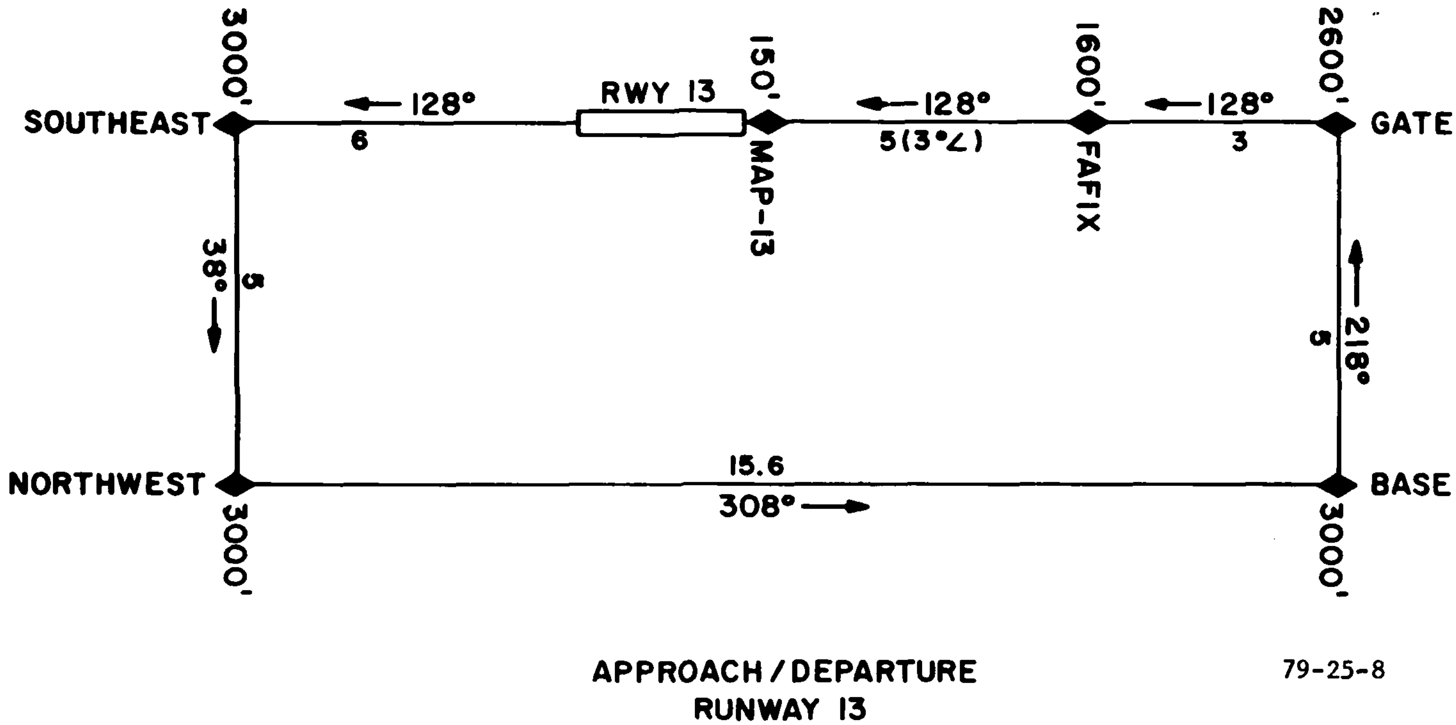


FIGURE 8. APPROACH/DEPARTURE PATTERN RUNWAY 13

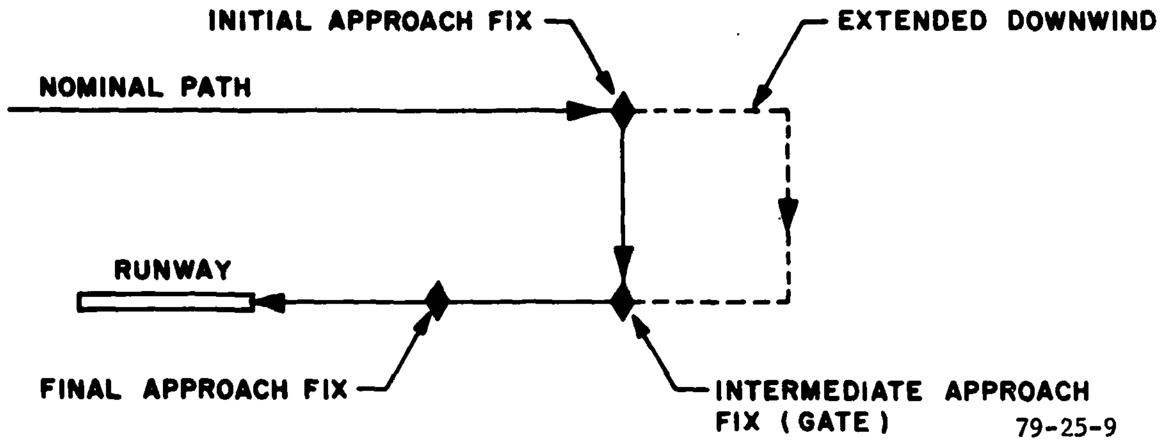


FIGURE 9. STANDARD EXTENDED PATTERN

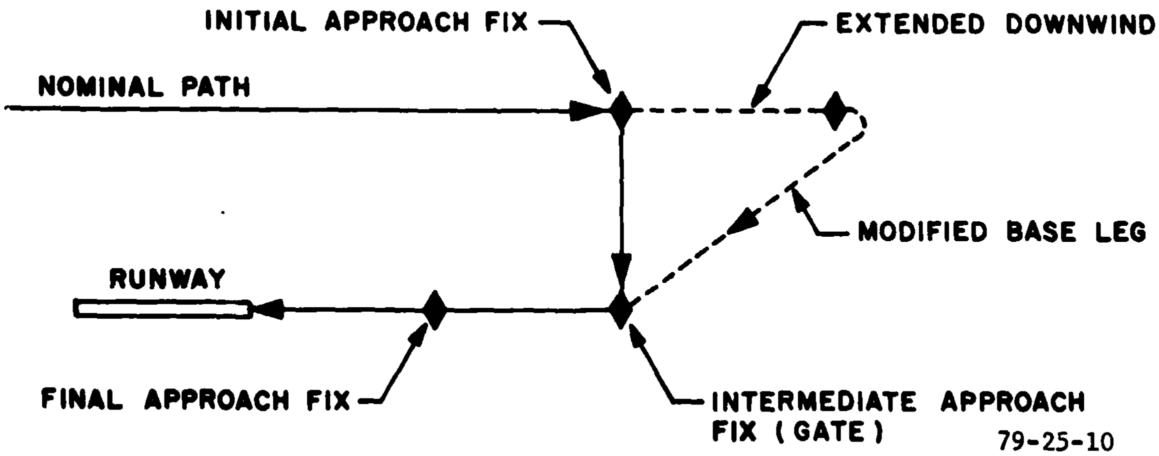


FIGURE 10. MODIFIED EXTENDED PATTERN

ALPHA TWO RNAV DEPARTURE

SOUTH DEPARTURE –

RUNWAY 4: PROCEED DIRECT TO BRAVO W/P, DIRECT ROMEO W/P, DIRECT SIERRA W/P, DIRECT TANGO W/P. CROSS BRAVO W/P AT OR ABOVE 1200'. CROSS ROMEO W/P AT OR ABOVE 3000', THEN CLIMB TO 10,500' OR AS ASSIGNED.

RUNWAYS 8, 13, 22: TURN LEFT DIRECT TO BRAVO W/P, DIRECT ROMEO W/P, DIRECT SIERRA W/P, DIRECT TANGO W/P. CROSS BRAVO W/P AT OR ABOVE 1200'. CROSS ROMEO AT OR ABOVE 3000', THEN CLIMB TO 10,500' OR AS ASSIGNED.

RUNWAYS 26, 31: TURN RIGHT DIRECT TO BRAVO W/P, DIRECT ROMEO W/P, DIRECT SIERRA W/P, DIRECT TANGO W/P. CROSS BRAVO W/P AT OR ABOVE 1200'. CROSS ROMEO W/P AT OR ABOVE 3000', THEN CLIMB TO 10,500' OR AS ASSIGNED.

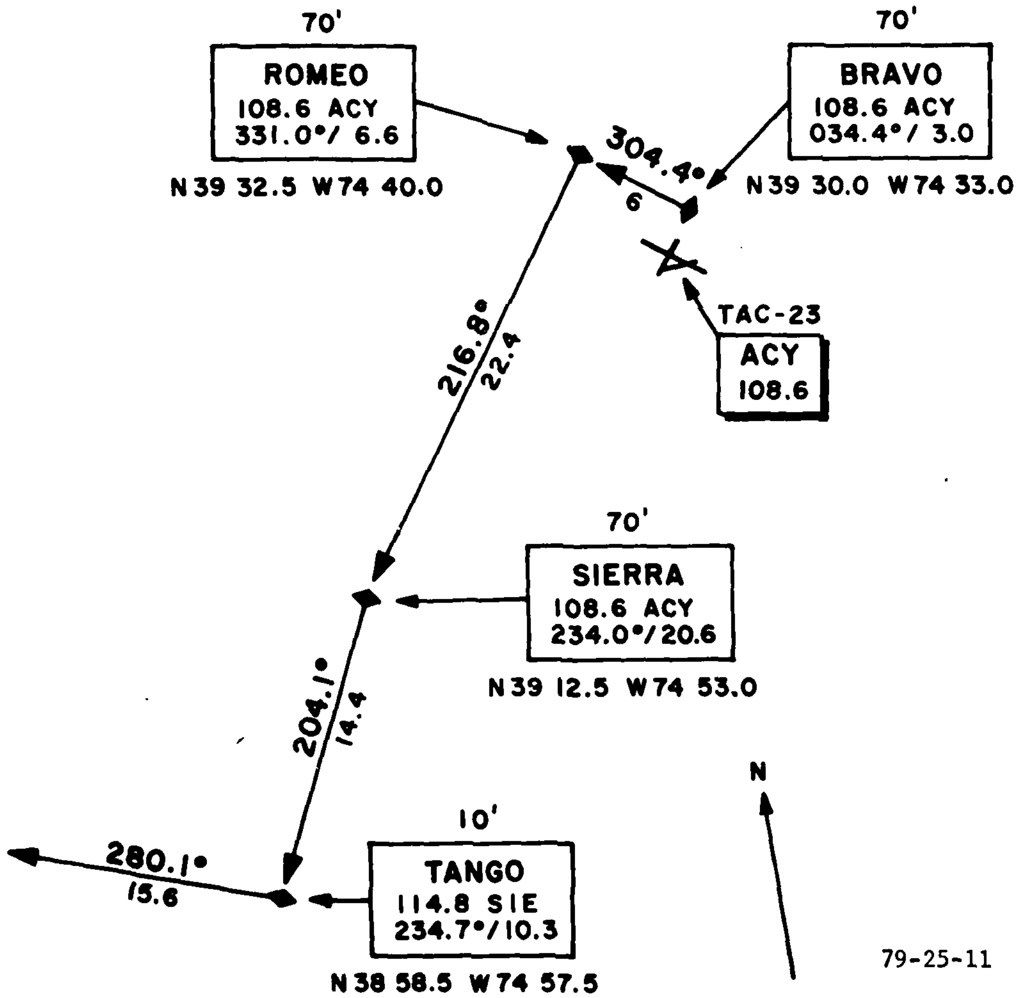


FIGURE 11. ALPHA TWO RNAV DEPARTURE

ALPHA TWO RNAV ARRIVAL

SOUTH ARRIVAL –
RUNWAY 4: UNIFORM W/P, DIRECT VICTOR W/P, DIRECT GOLF W/P, DIRECT HOTEL W/P. CROSS UNIFORM W/P AT 10,500', CROSS GOLF W/P AT OR ABOVE 3,500', CROSS HOTEL W/P AT 3,500'.
RUNWAY 13: UNIFORM W/P, DIRECT VICTOR W/P, DIRECT GOLF W/P, DIRECT BALTIC W/P. CROSS GOLF W/P AT OR ABOVE 3,200', CROSS BALTIC W/P AT 3,200'.

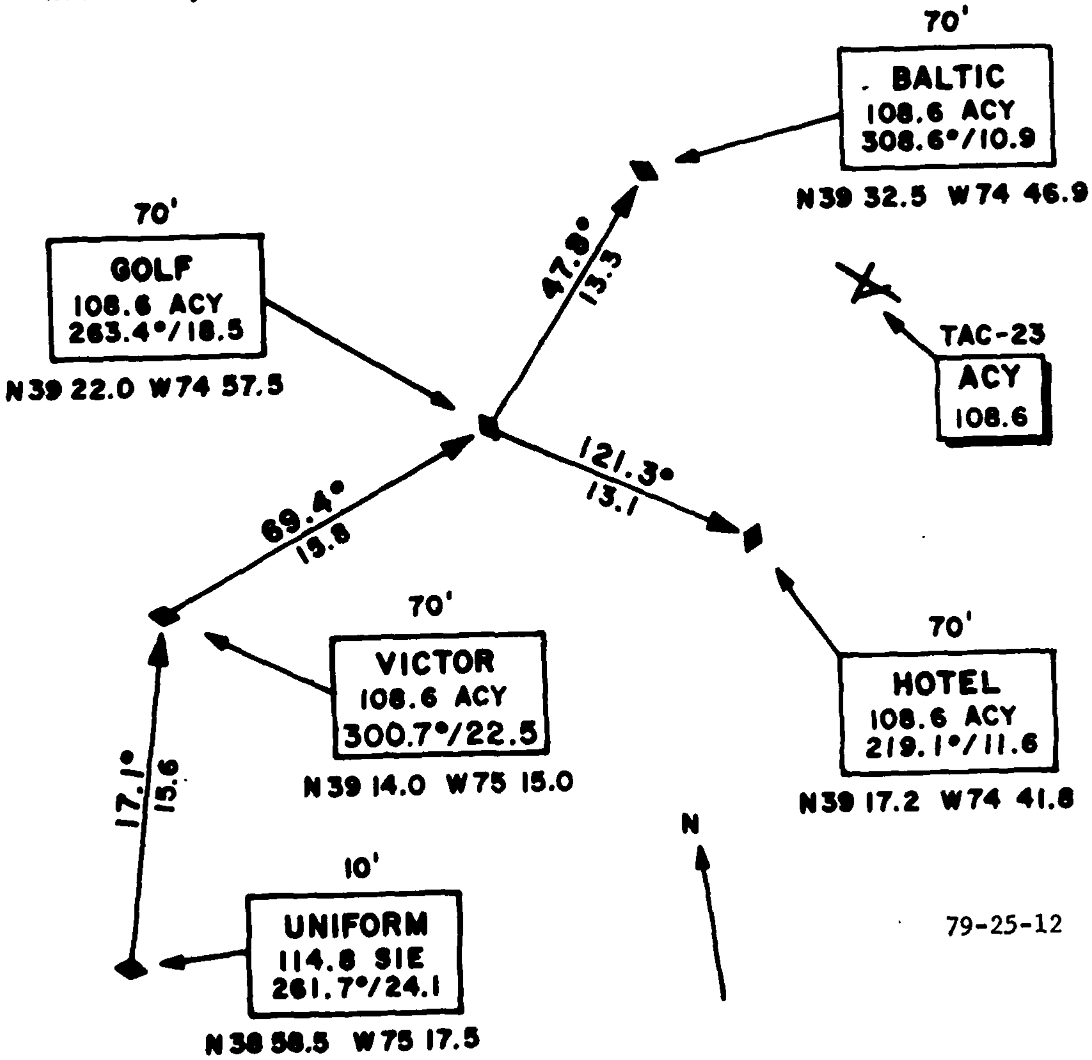


FIGURE 12. ALPHA TWO RNAV ARRIVAL

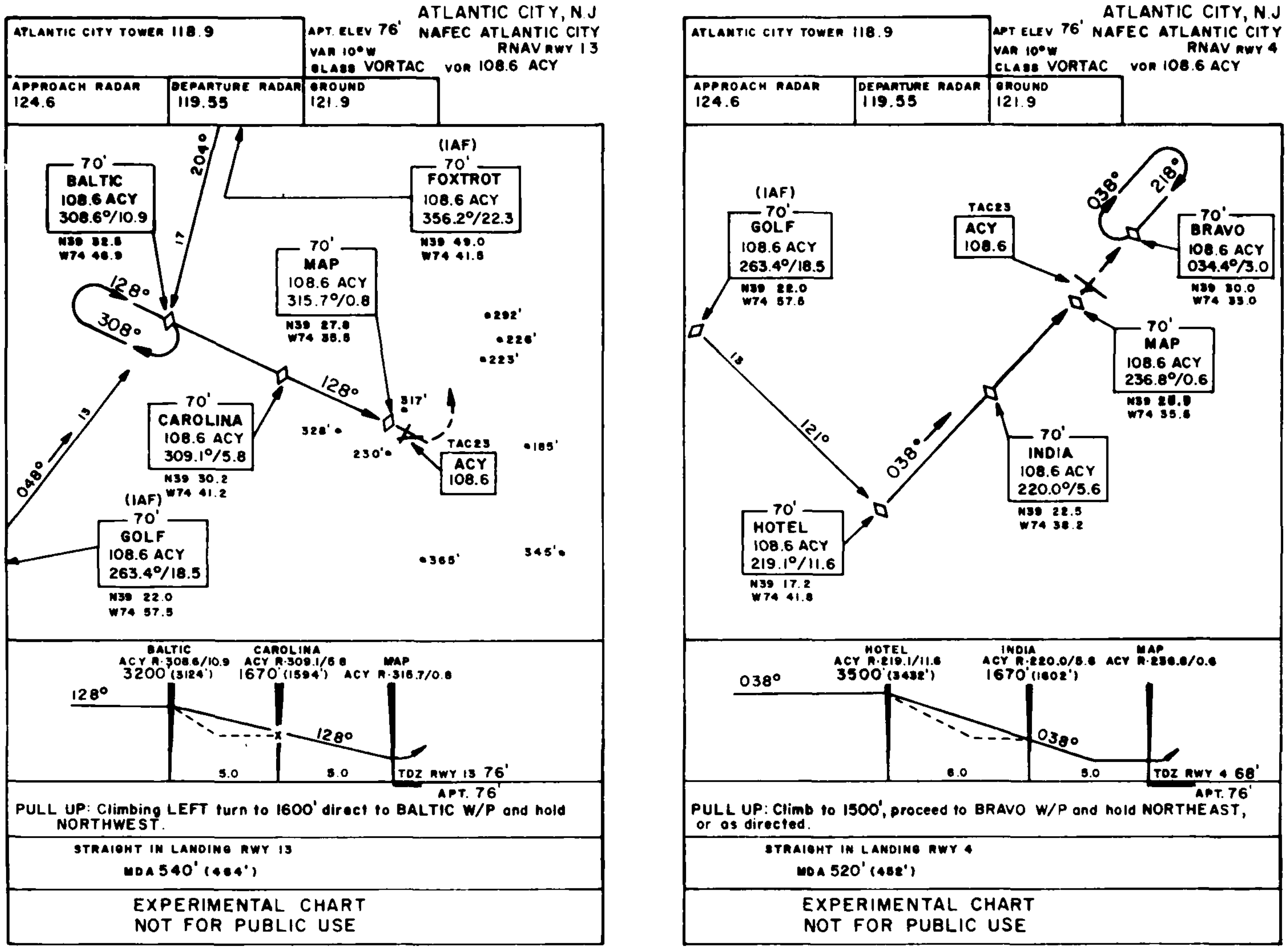


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FIGURE 13. NAFEC APPROACH PLATES TO RUNWAYS 13 AND 4

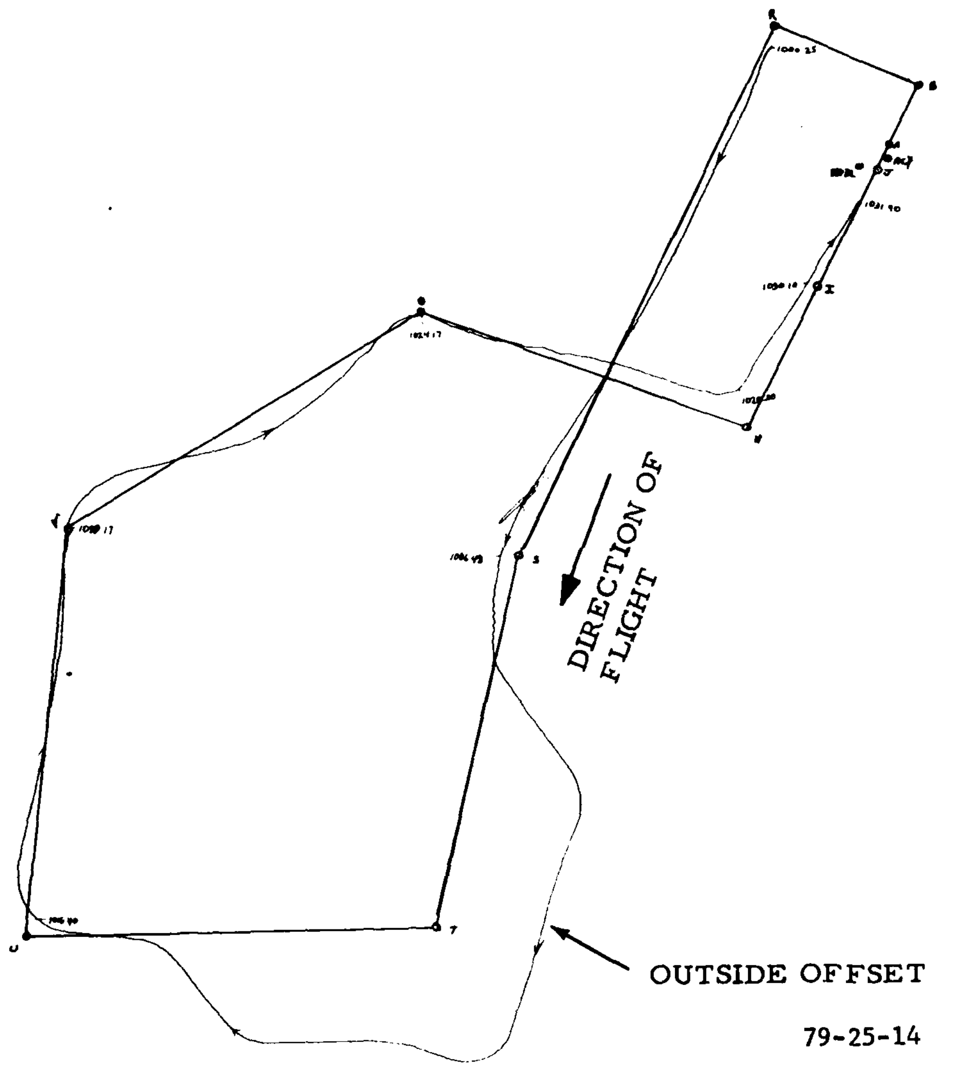

FIGURE 14. A2 ROUTE RADAR PLOT WITH A 4 NMI OUTSIDE OFFSET

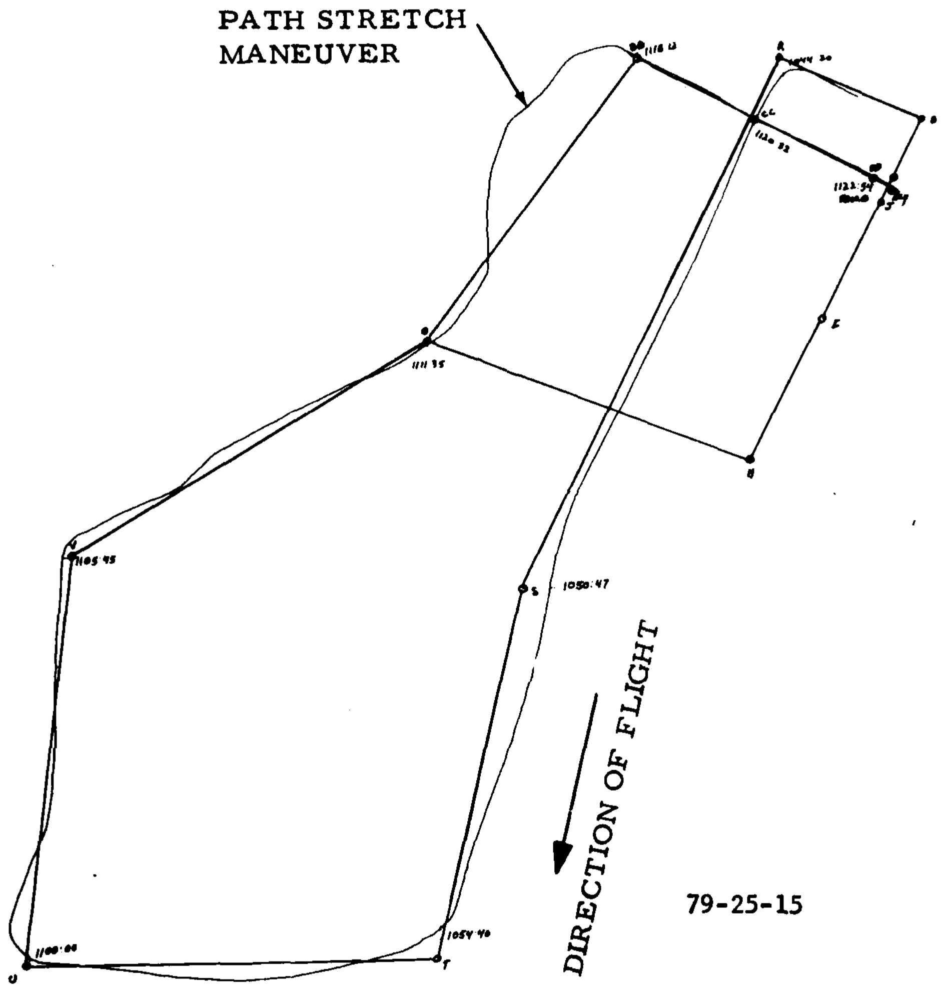

FIGURE 15. A2 ROUTE RADAR PLOT WITH A 2 NMI LEFT OFFSET

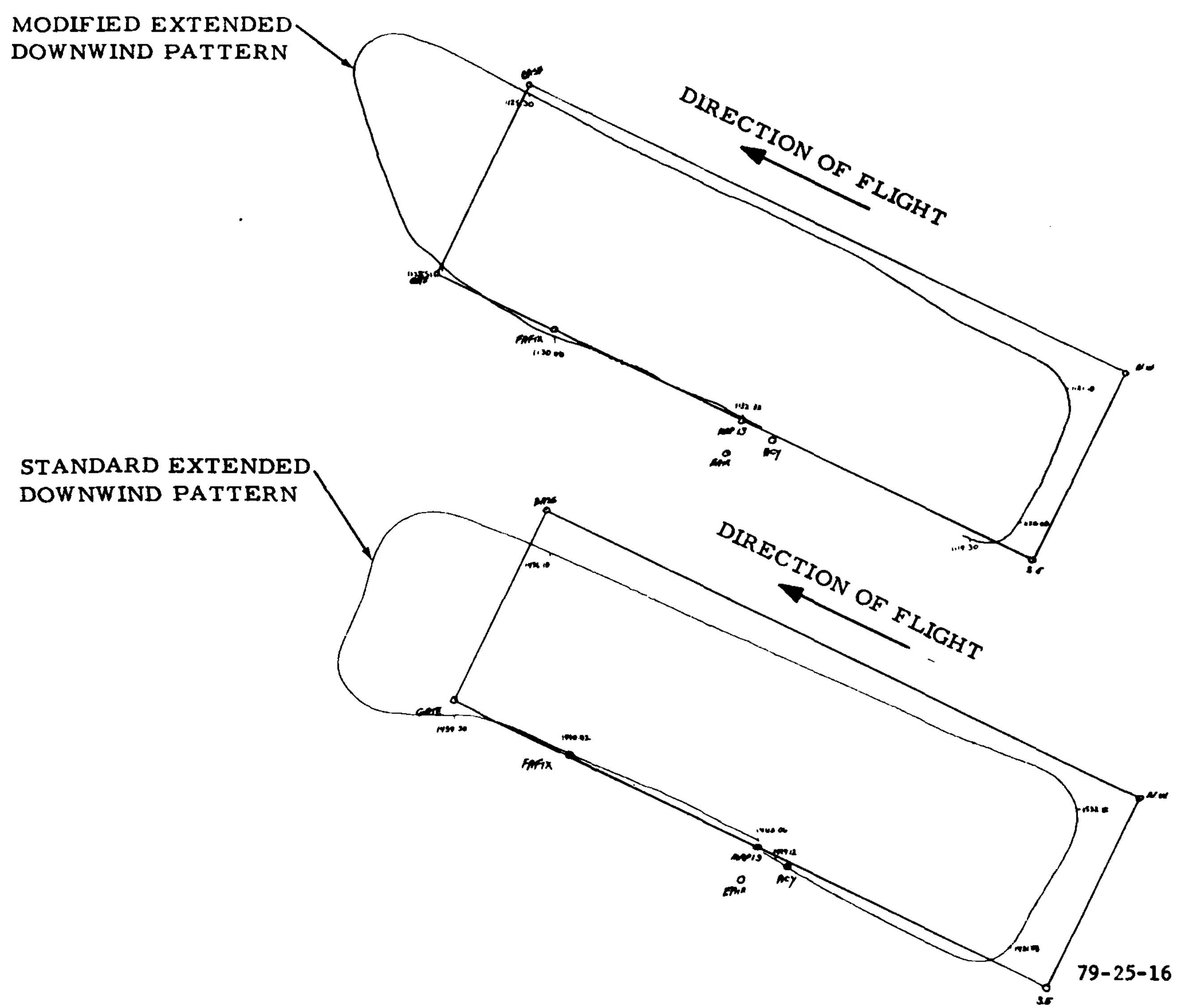

FIGURE 16. APPROACH PATTERN RADAR PLOT OF EXTENDED DOWNWIND LEGS

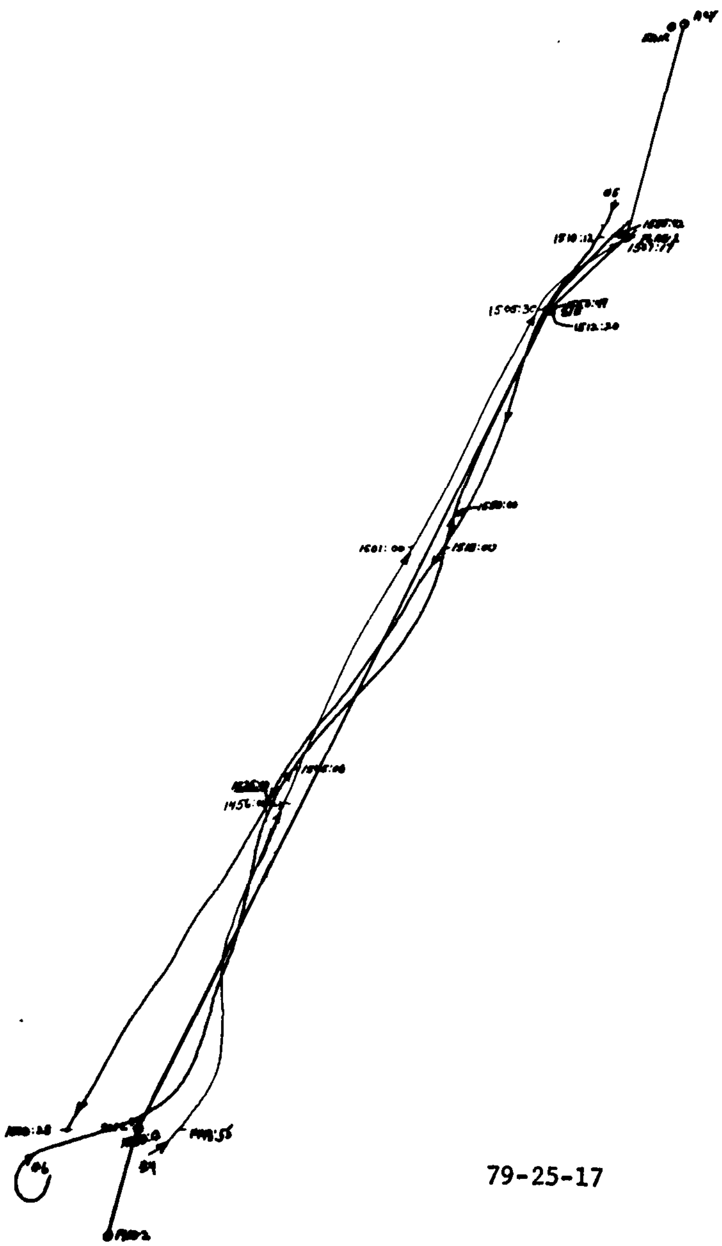

FIGURE 17. RADAR TRACKED PLOT OF HIGH ALTITUDE PATTERN (25,000 ft m.s.l.)

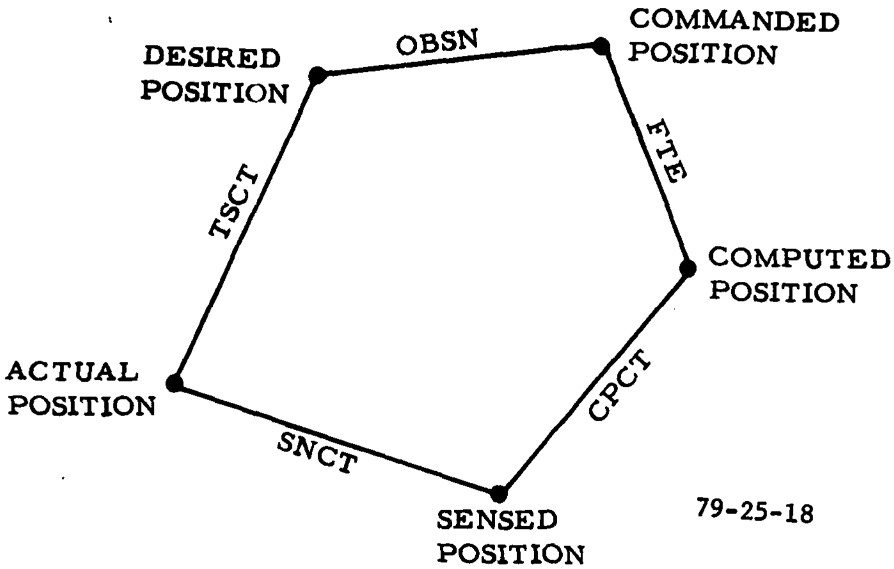

FIGURE 18. TOTAL SYSTEM ERROR PARADIGM

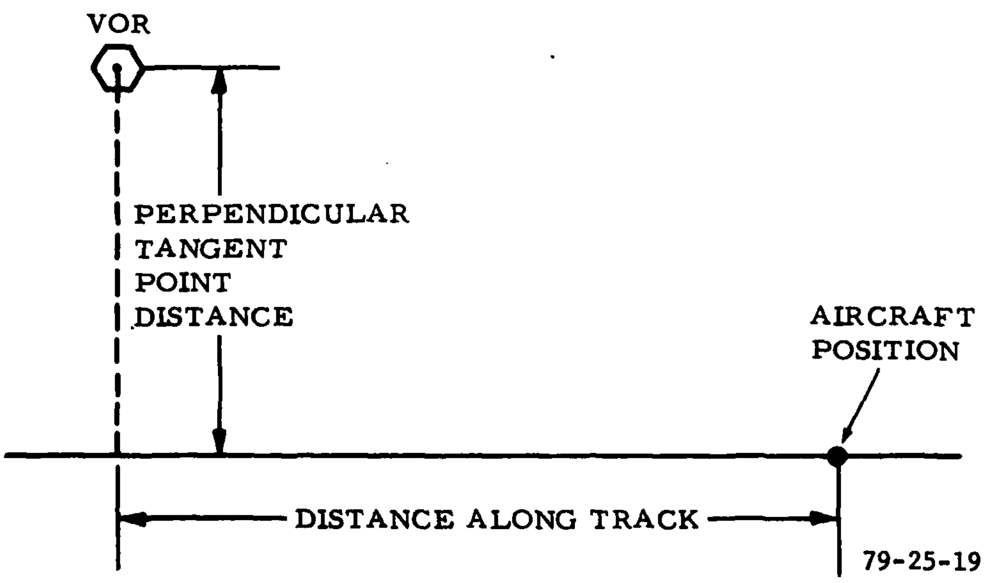

FIGURE 19. TANGENT POINT AND ALONG-TRACK DISTANCES

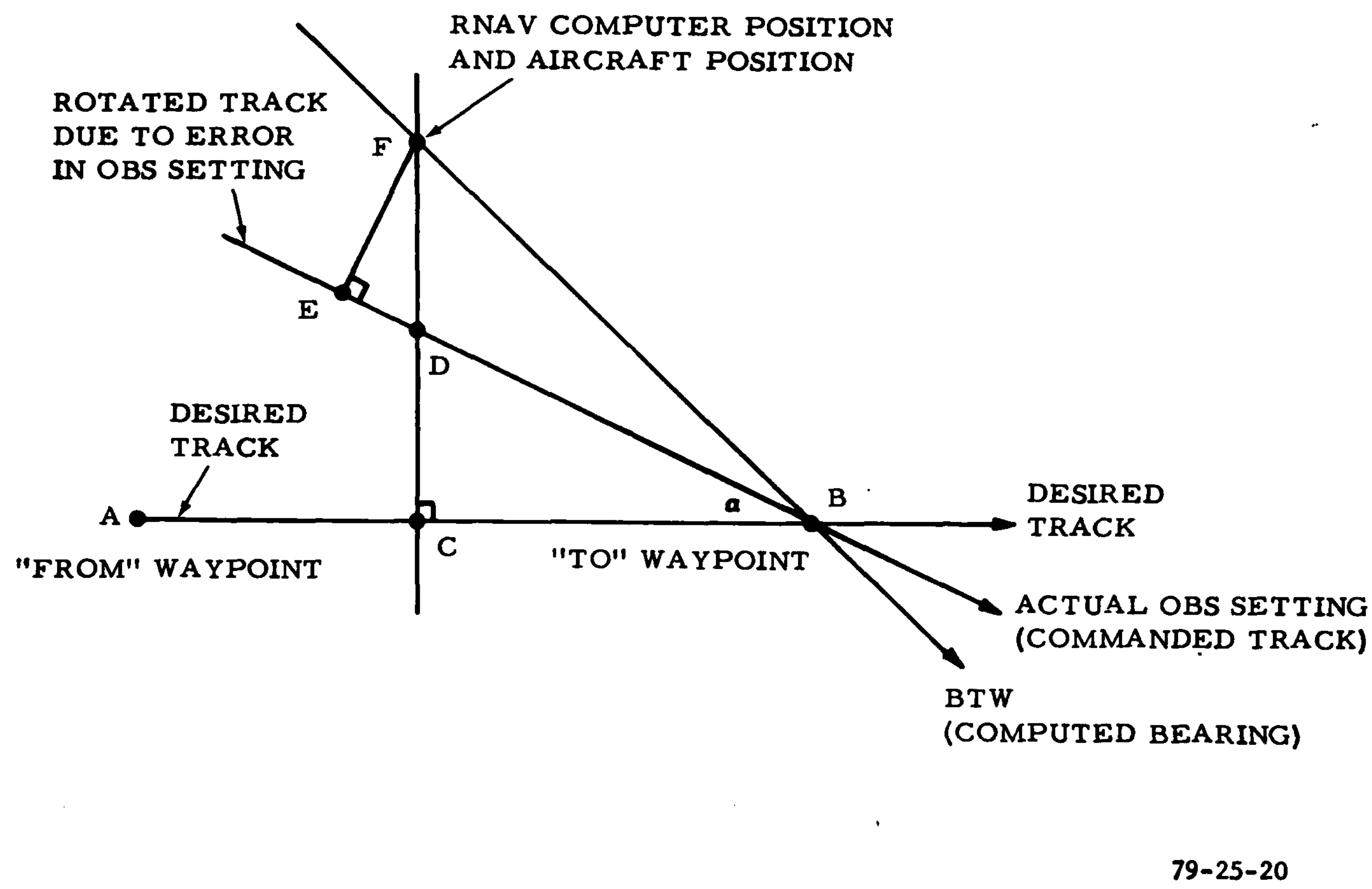

FIGURE 20. OBS ERROR GEOMETRY

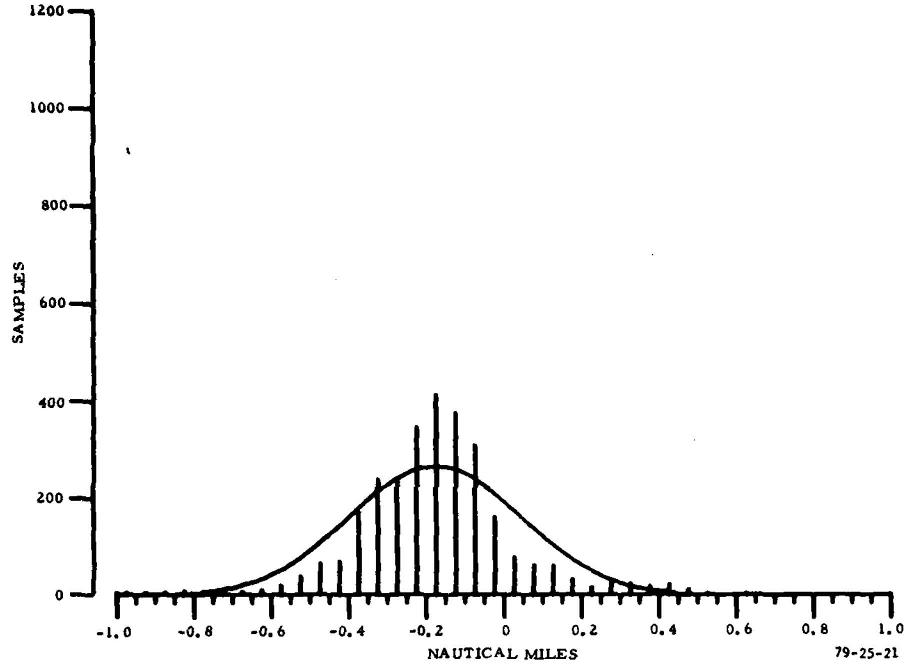

FIGURE 21. APPROACH AREA SENSOR CROSSTRACK ERROR HISTOGRAM

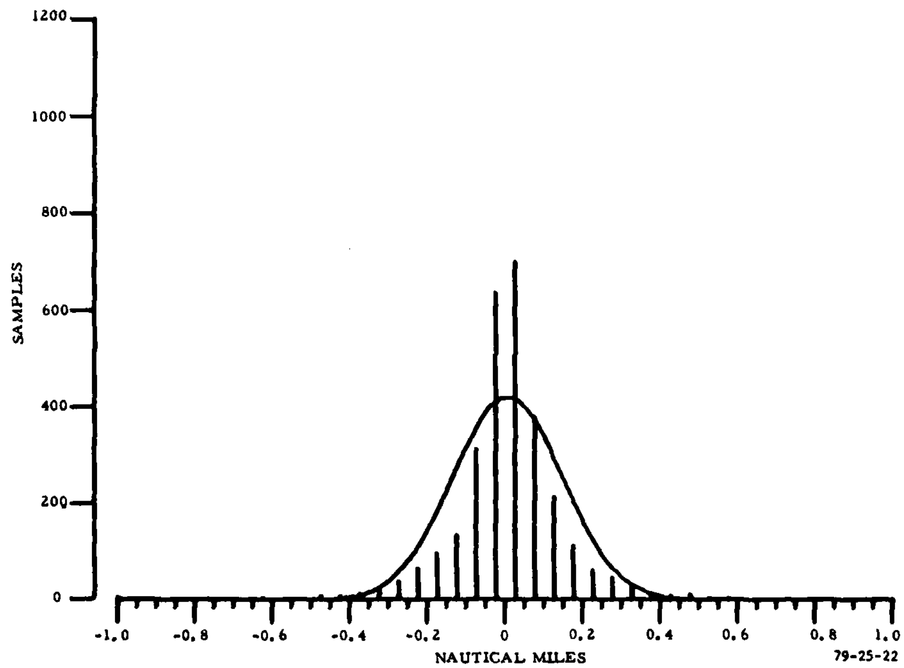

FIGURE 22. APPROACH AREA COMPUTER CROSSTRACK ERROR HISTOGRAM

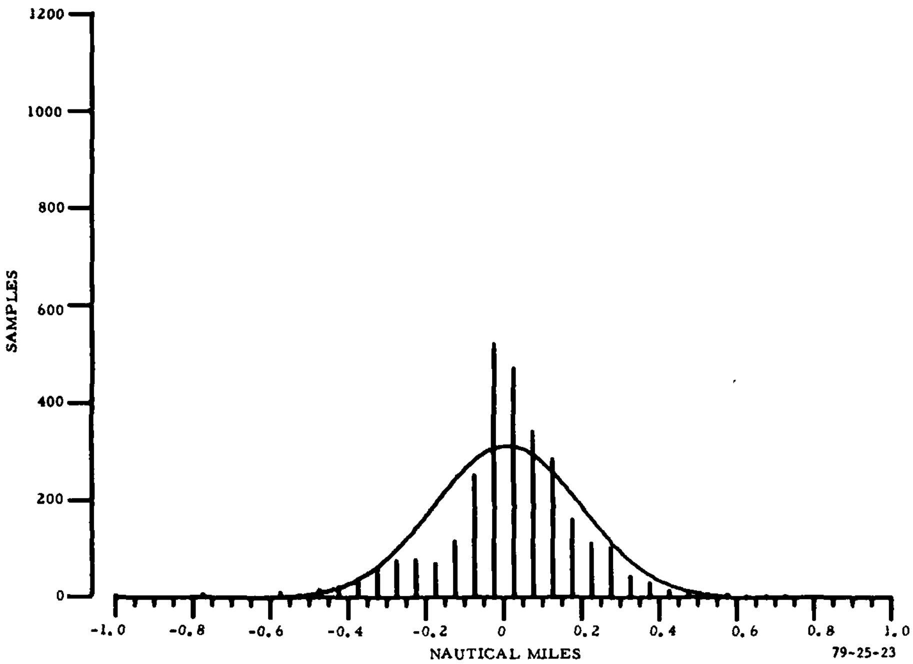

FIGURE 23. APPROACH AREA FLIGHT TECHNICAL ERROR HISTOGRAM

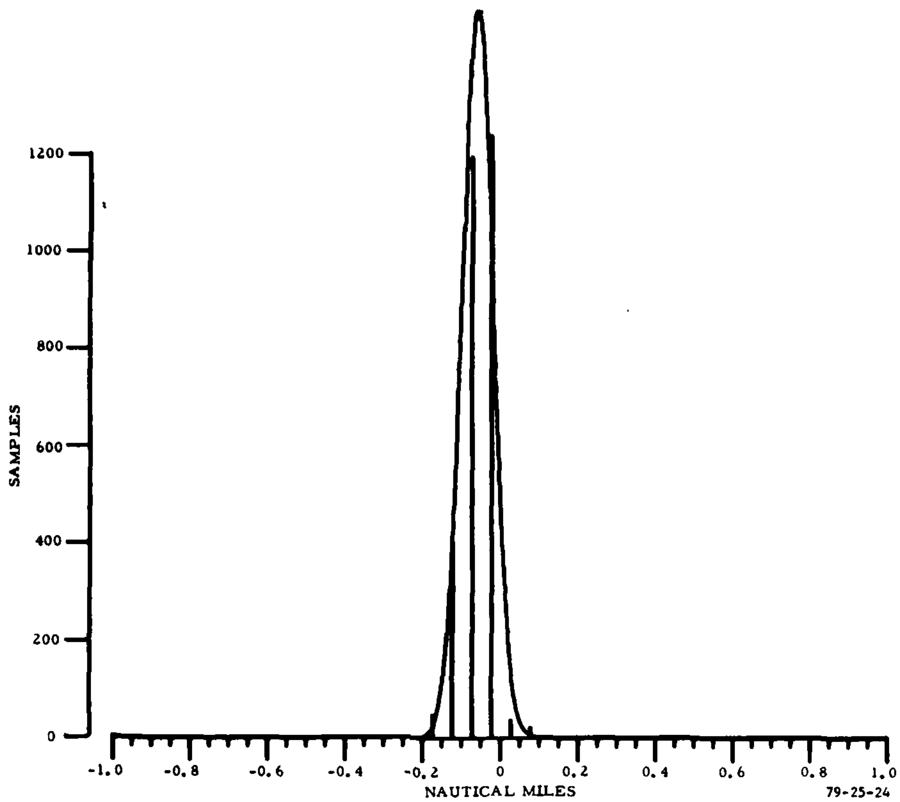

FIGURE 24. APPROACH AREA OMNIBEARING SELECTOR CROSSTRACK ERROR HISTOGRAM

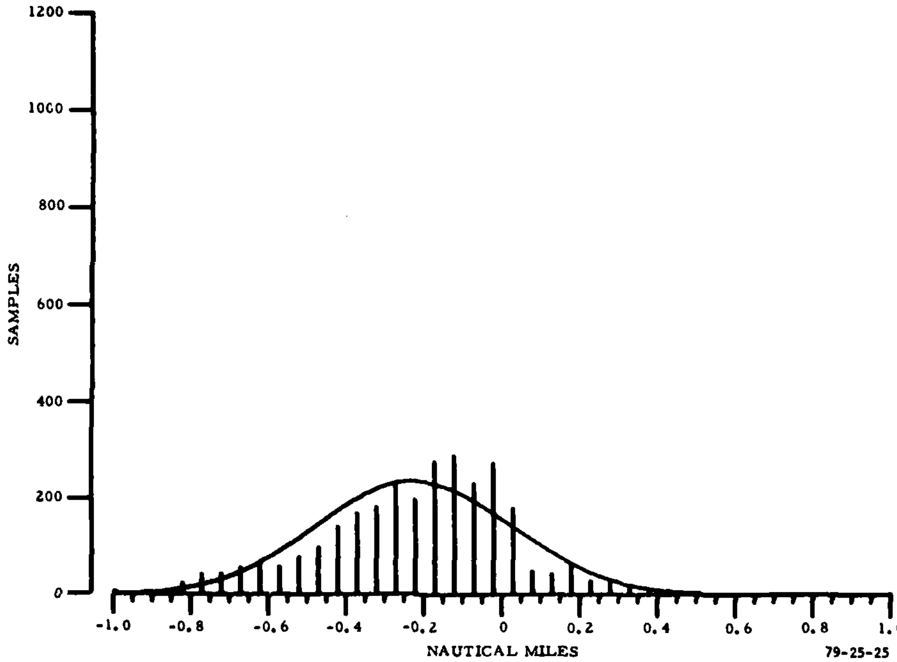

FIGURE 25. APPROACH AREA TOTAL SYSTEM CROSSTRACK ERROR HISTOGRAM

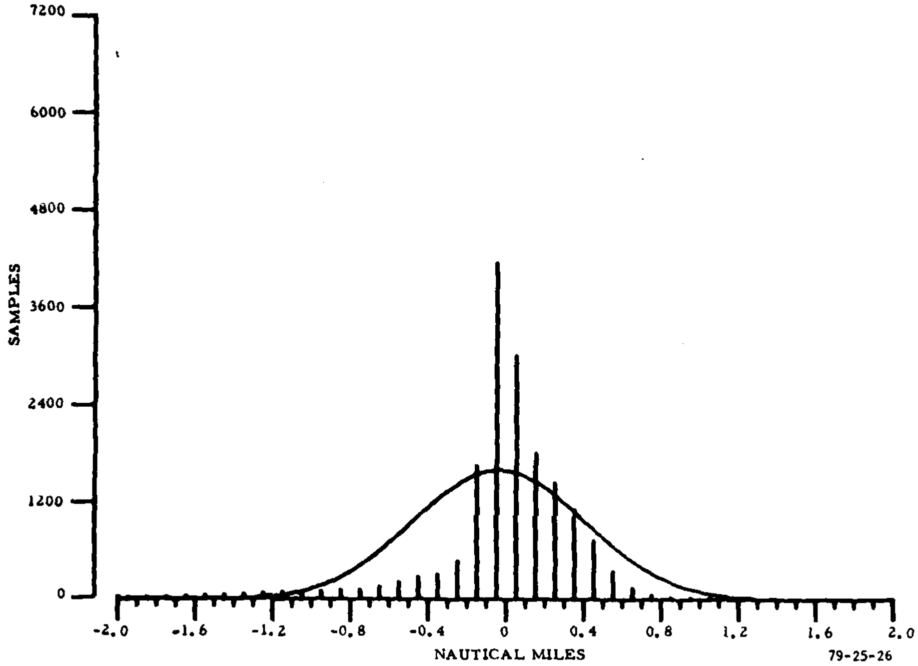

FIGURE 26. TERMINAL AREA SENSOR CROSSTRACK ERROR HISTOGRAM

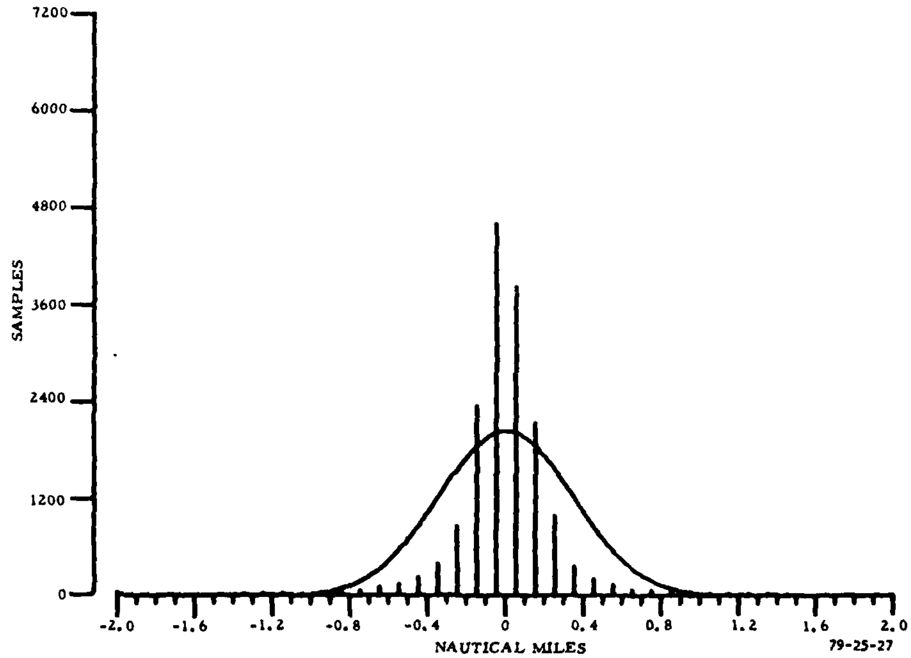

FIGURE 27. TERMINAL AREA COMPUTER CROSSTRACK ERROR HISTOGRAM

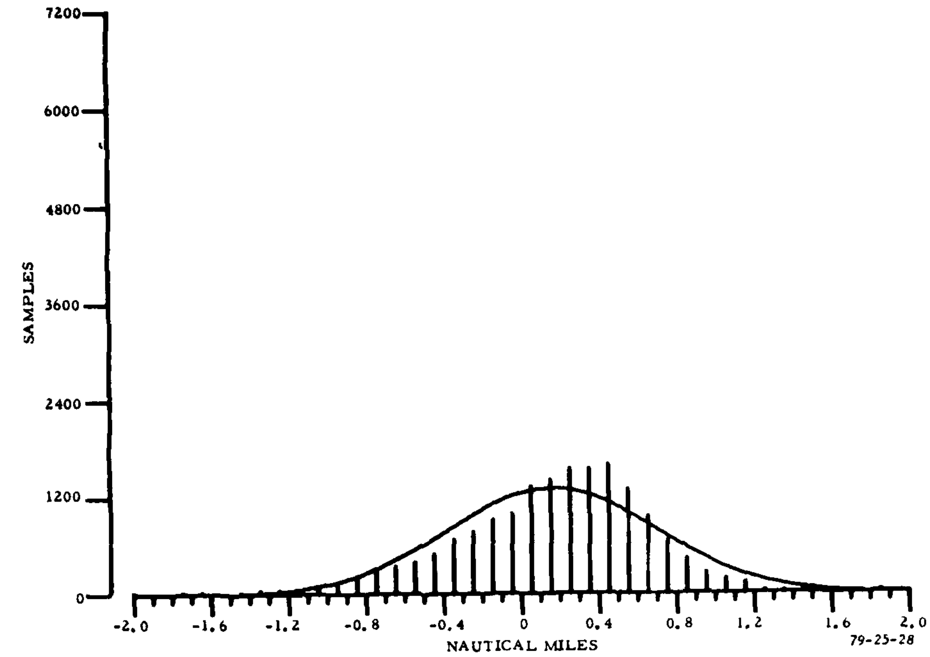

FIGURE 28. TERMINAL AREA FLIGHT TECHNICAL ERROR HISTOGRAM

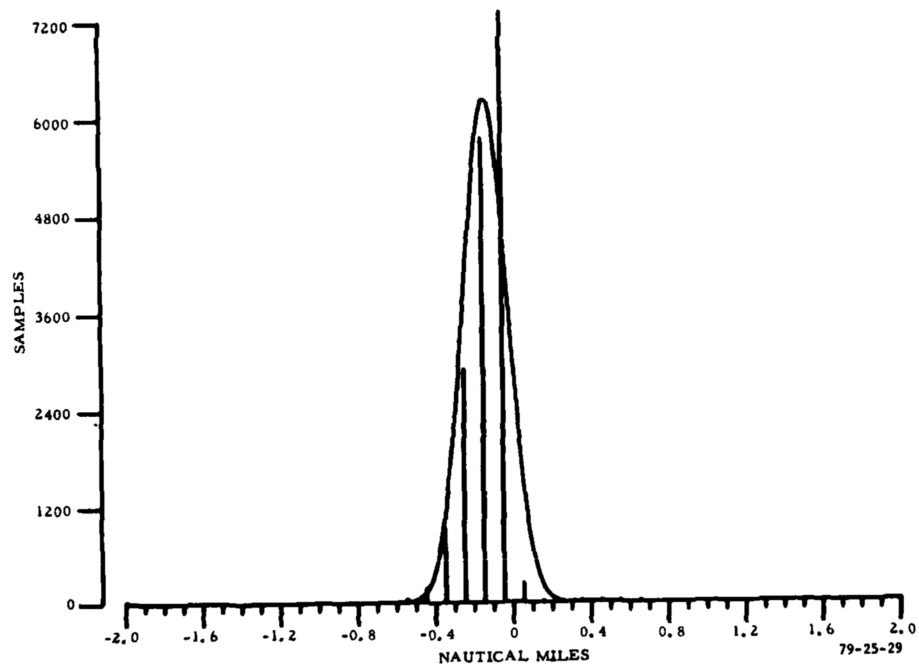

FIGURE 29. TERMINAL AREA OMNIBEARING SELECTOR CROSSTRACK ERROR HISTOGRAM

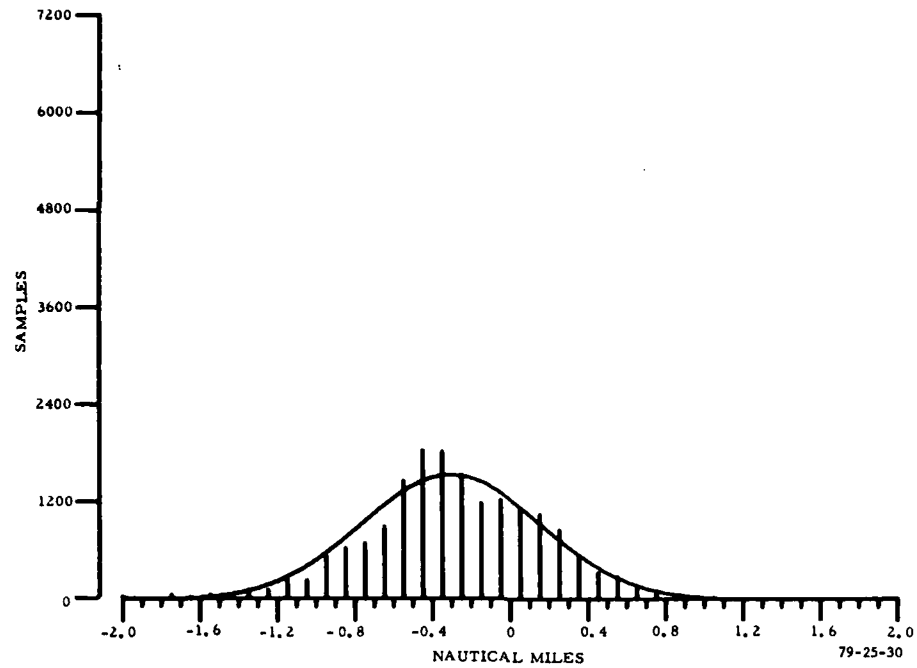

FIGURE 30. TERMINAL AREA TOTAL SYSTEM CROSSTRACK ERROR HISTOGRAM

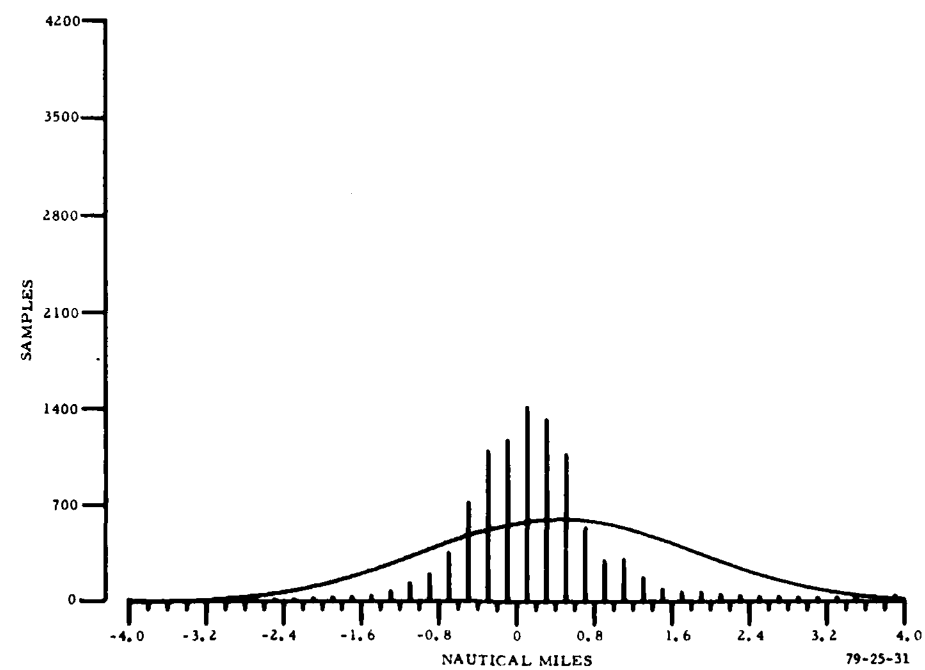

FIGURE 31. EN ROUTE AREA SENSOR CROSSTRACK ERROR HISTOGRAM

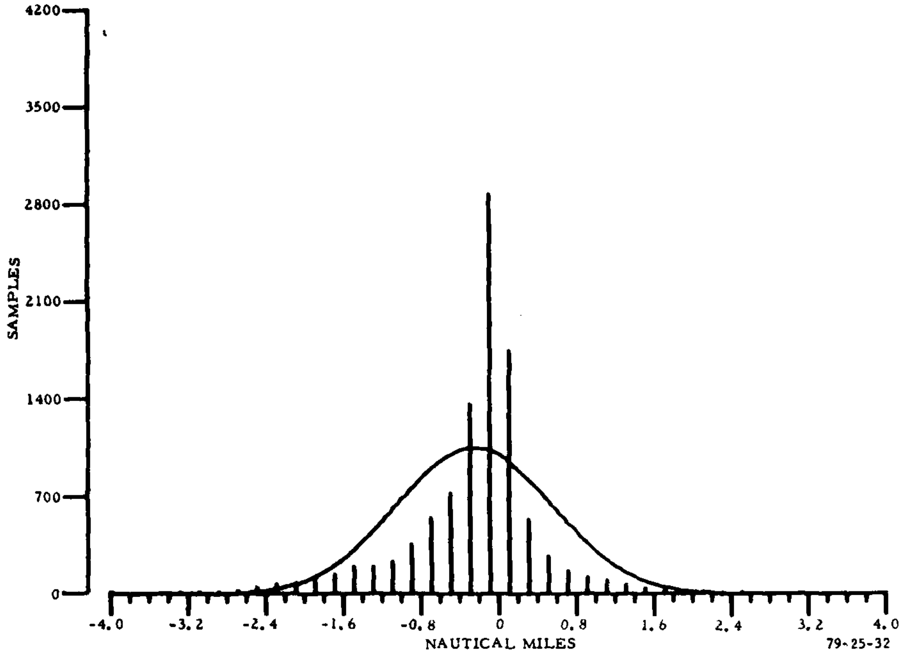

FIGURE 32. EN ROUTE AREA COMPUTER CROSSTRACK HISTOGRAM

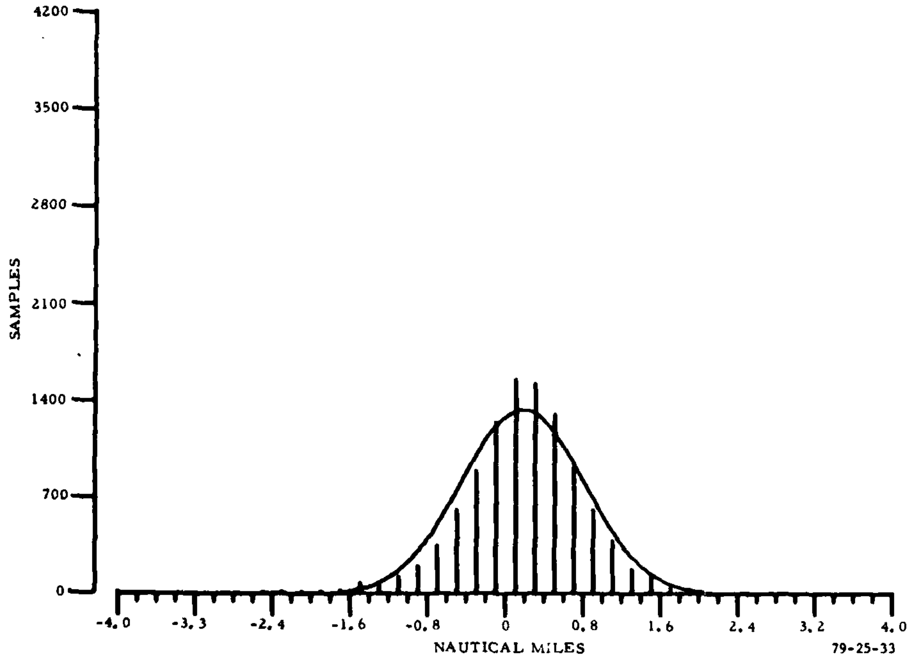

FIGURE 33. EN ROUTE AREA FLIGHT TECHNICAL ERROR HISTOGRAM

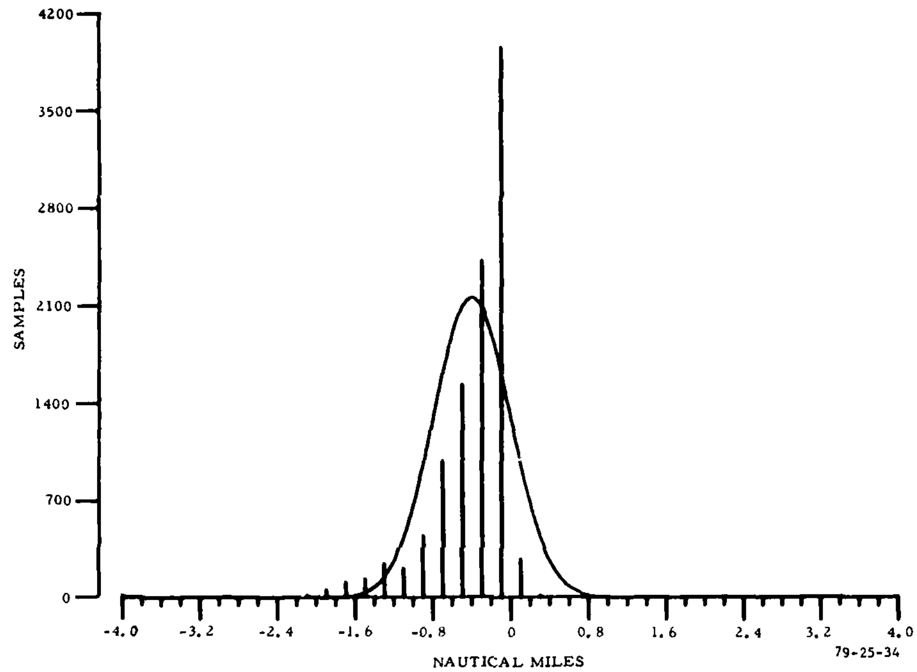

FIGURE 34. EN ROUTE AREA OMNIBEARING SELECTOR CROSSTRACK HISTOGRAM

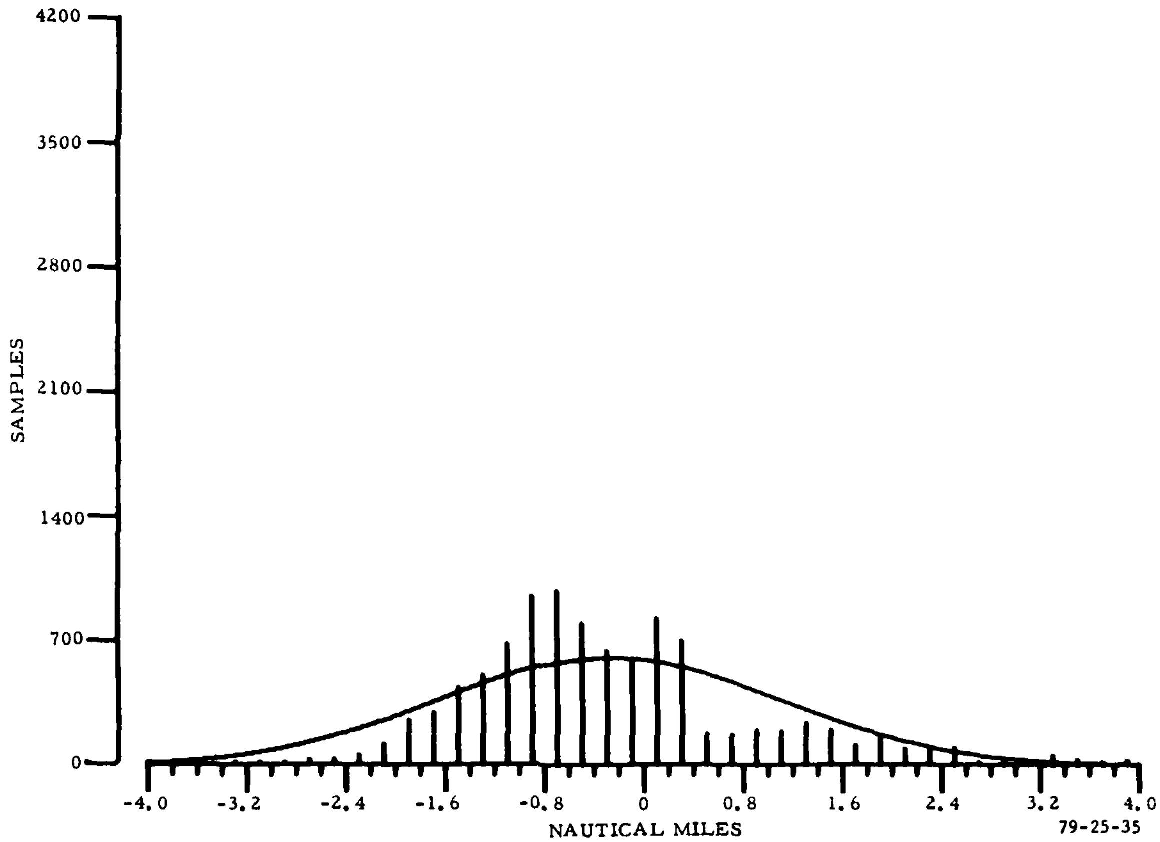

FIGURE 35. EN ROUTE AREA TOTAL SYSTEM CROSSTRACK ERROR HISTOGRAM

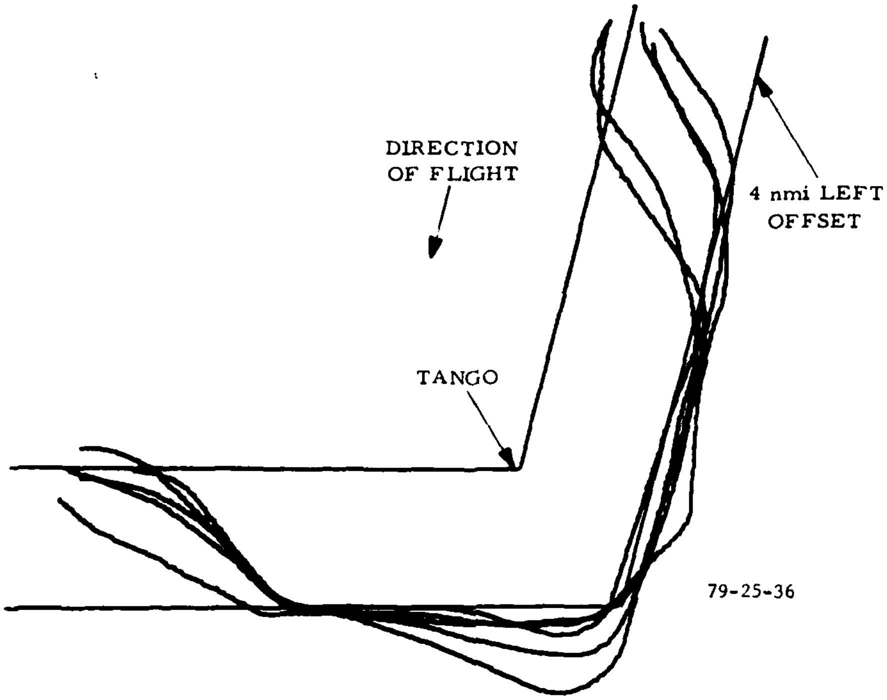

FIGURE 36. FOUR-MILE LEFT (OUTSIDE) OFFSET

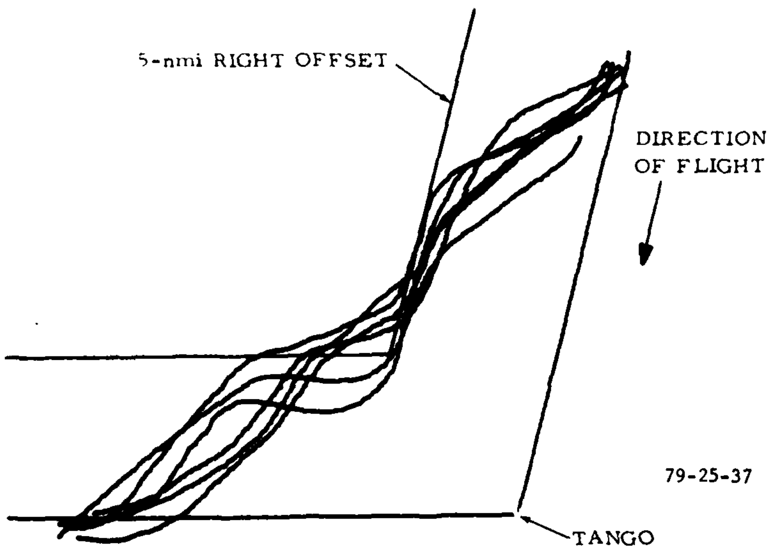

FIGURE 37. FIVE-MILE RIGHT (INSIDE) OFFSET

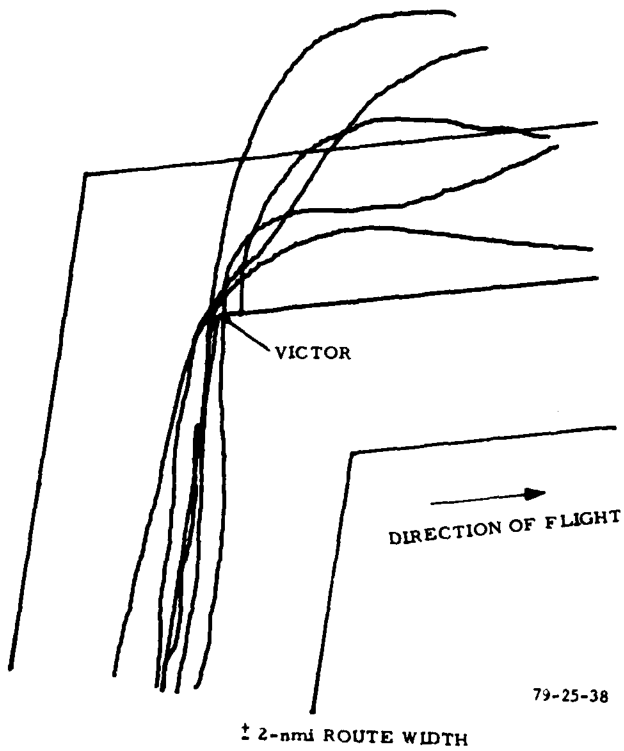

FIGURE 38. TURN AT VICTOR DIRECT TO HOTEL

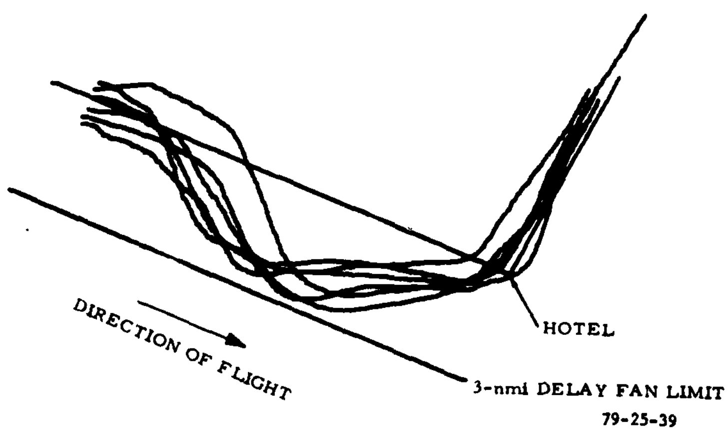

FIGURE 39. THREE-MILE RIGHT DELAY FAN

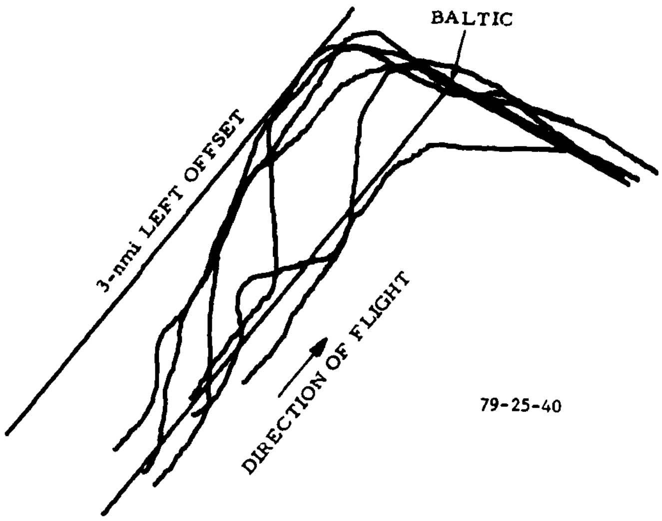

FIGURE 40. THREE-MILE LEFT OFFSET PATH STRETCH MANEUVER

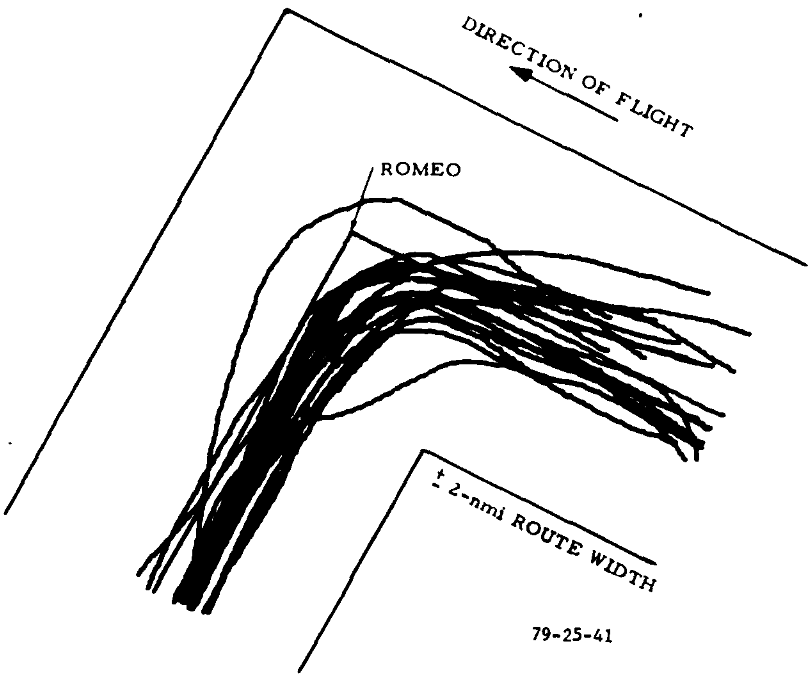

FIGURE 41. WAYPOINT ROMEO TURN PERFORMANCE

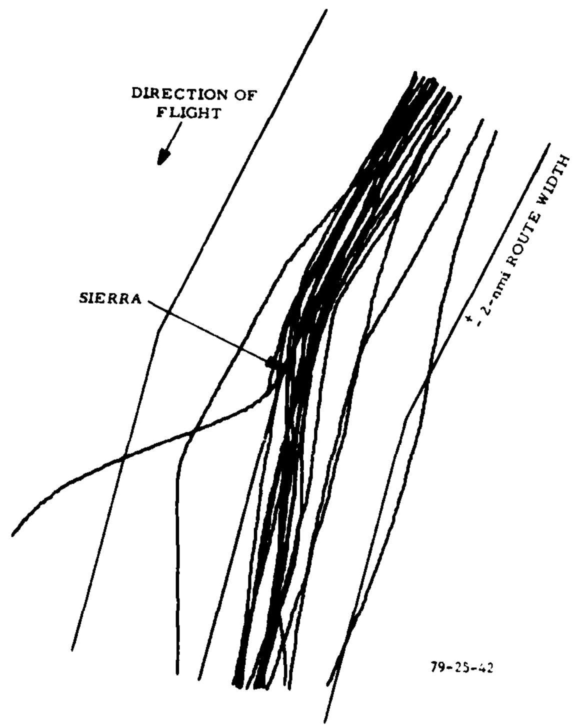

FIGURE 42. WAYPOINT SIERRA TURN PERFORMANCE

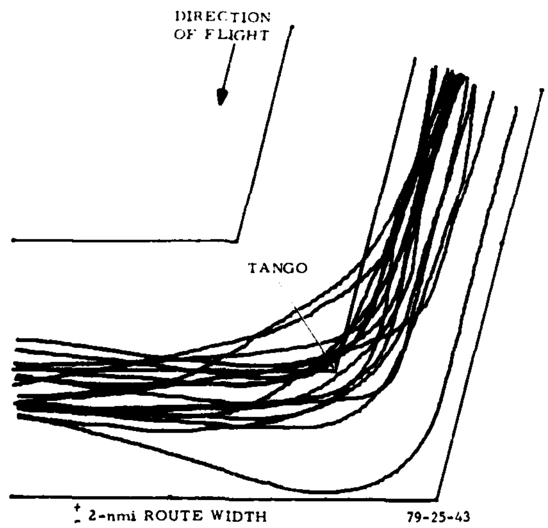

FIGURE 43. WAYPOINT TANGO TURN PERFORMANCE

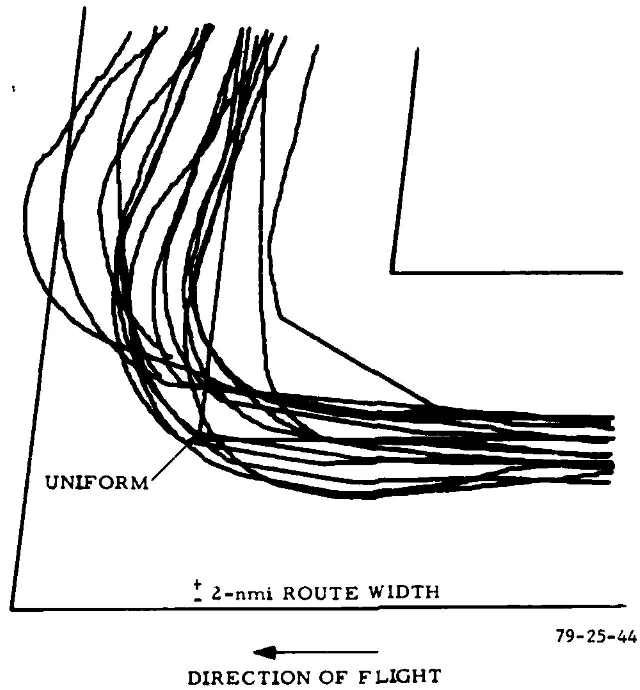

FIGURE 44. WAYPOINT UNIFORM (NORMAL) TURN PERFORMANCE

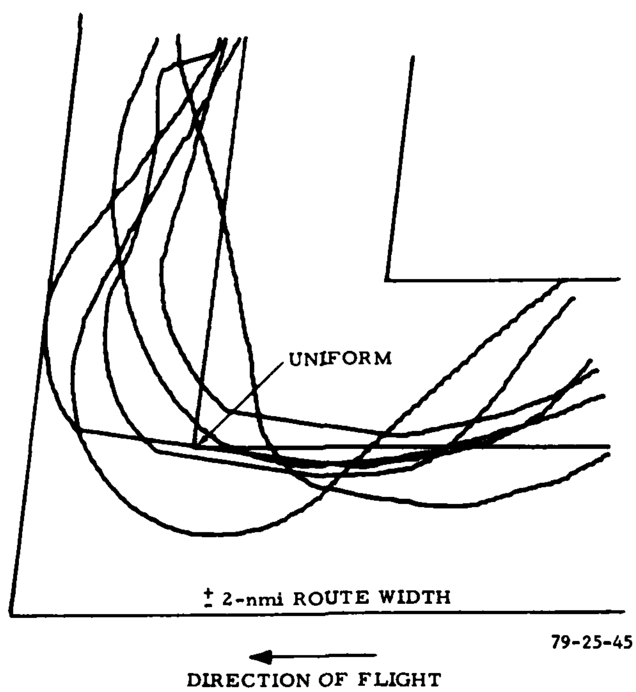

FIGURE 45. WAYPOINT UNIFORM (INSIDE OFFSET) TURN PERFORMANCE

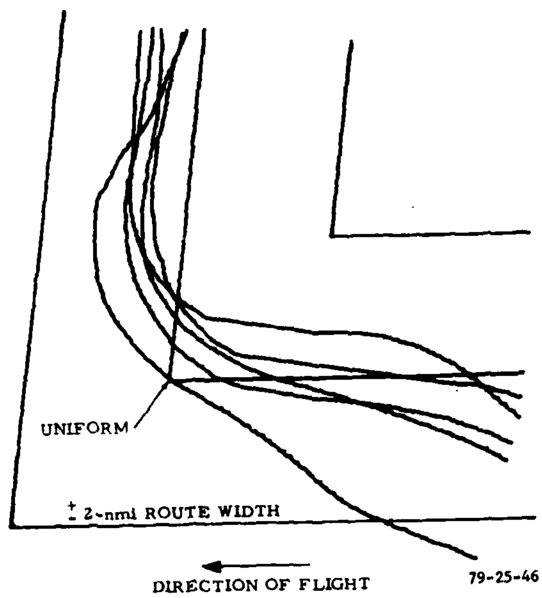

FIGURE 46. WAYPOINT UNIFORM (OUTSIDE OFFSET) TURN PERFORMANCE

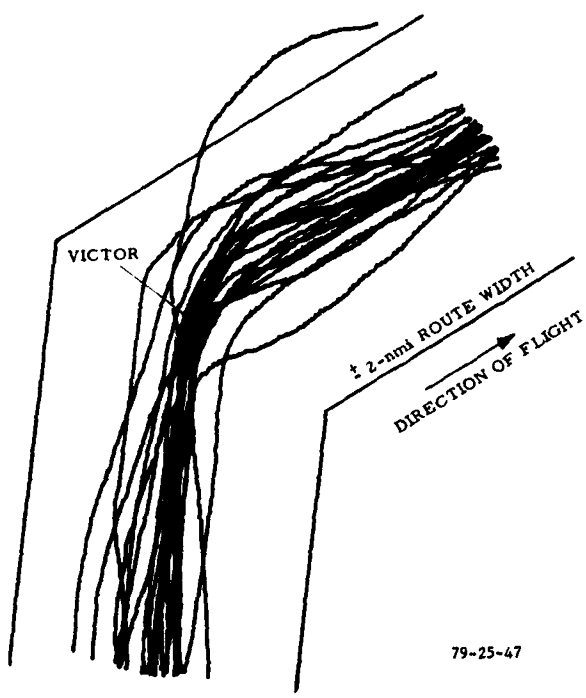

FIGURE 47. WAYPOINT VICTOR TURN PERFORMANCE

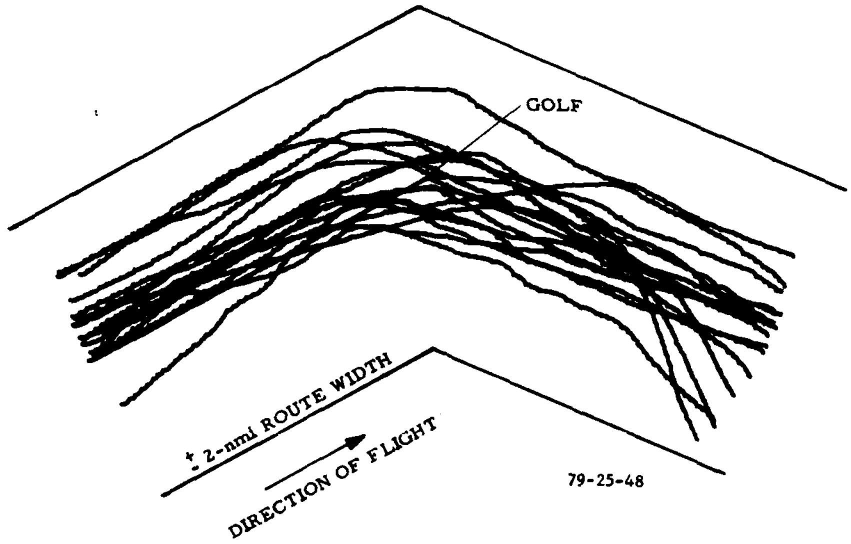

FIGURE 48. WAYPOINT GOLF (RUNWAY 4) TURN PERFORMANCE

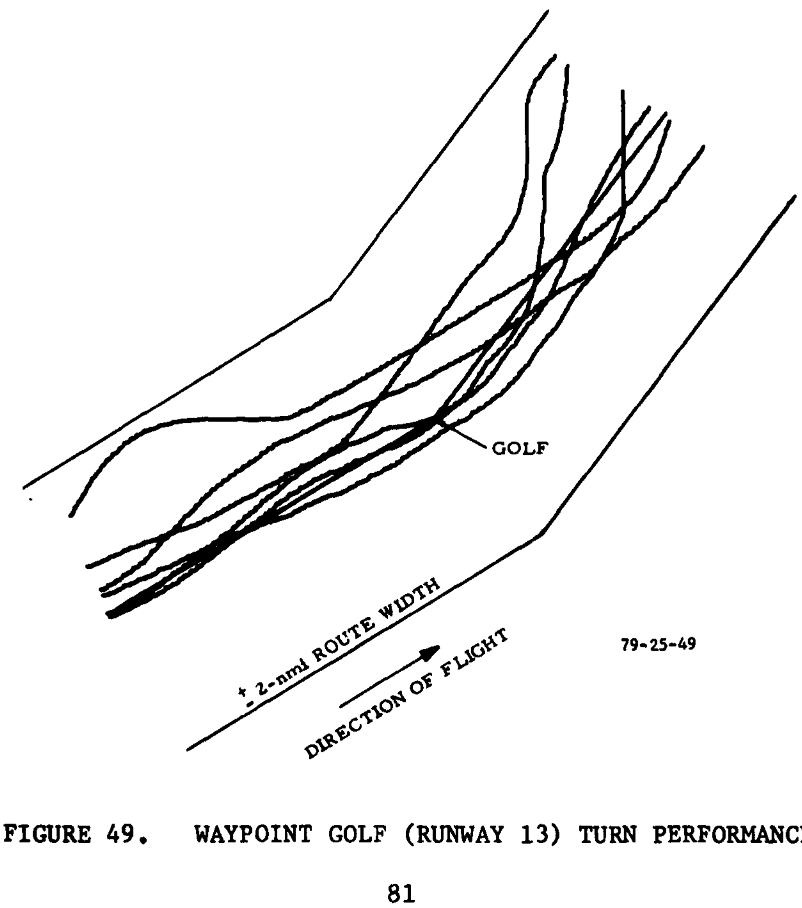

FIGURE 49. WAYPOINT GOLF (RUNWAY 13) TURN PERFORMANCE

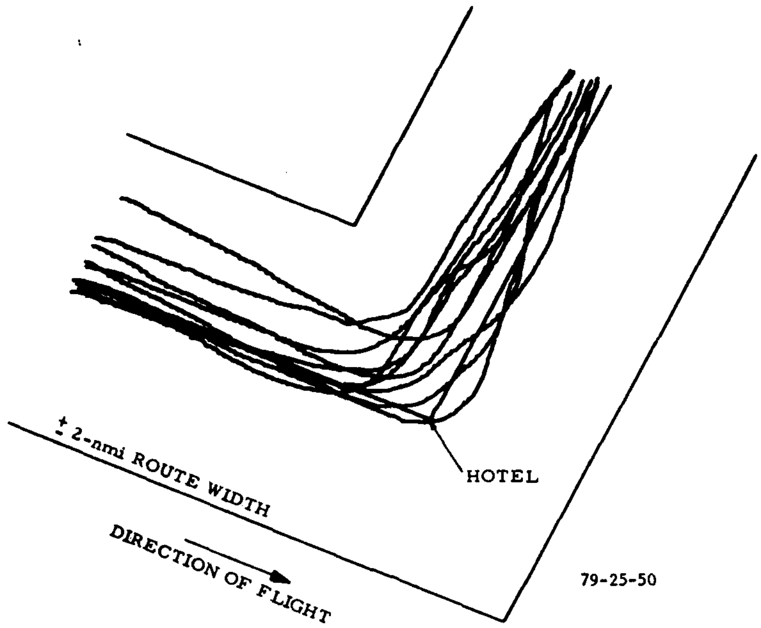

FIGURE 50. WAYPOINT HOTEL TURN PERFORMANCE

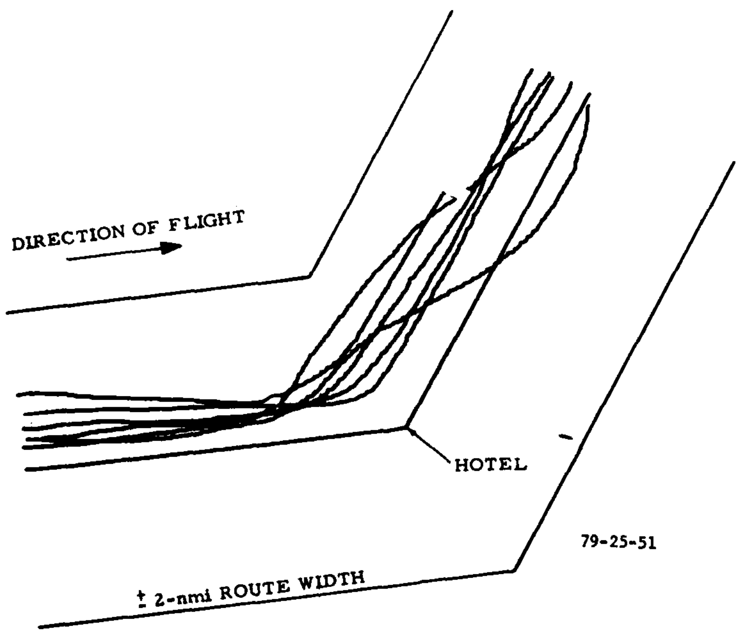

FIGURE 51. WAYPOINT HOTEL (DIRECT FROM VICTOR) TURN PERFORMANCE

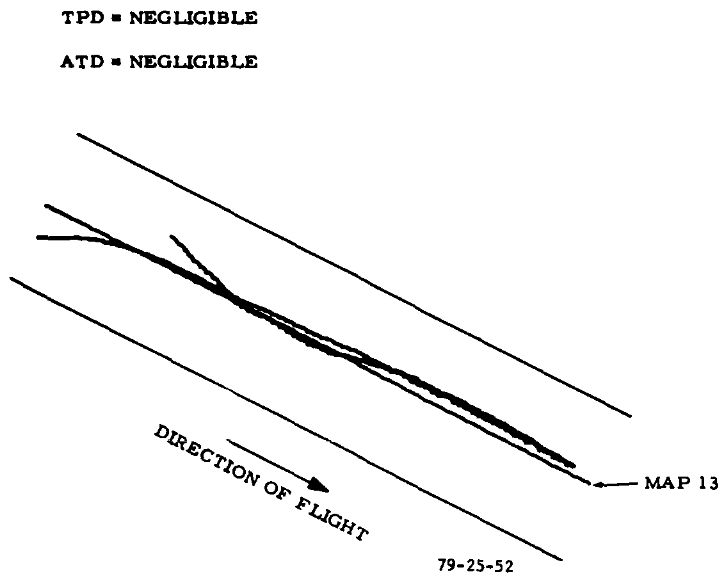

FIGURE 52. APPROACH PERFORMANCE RUNWAY 13, ACY

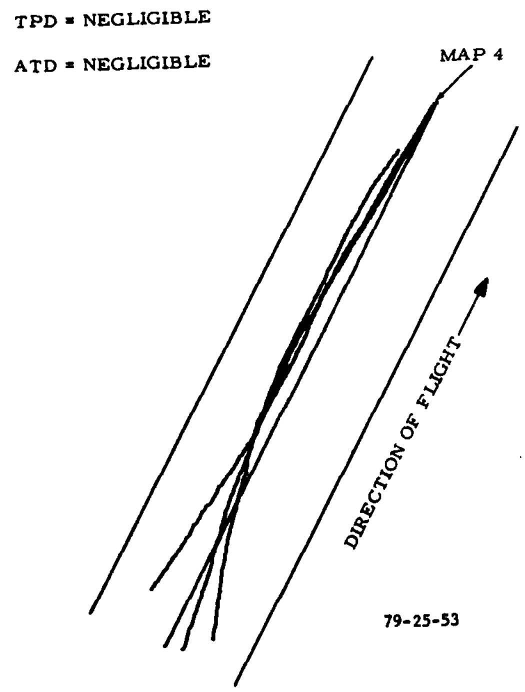

FIGURE 53. APPROACH PERFORMANCE RUNWAY 4, ACY

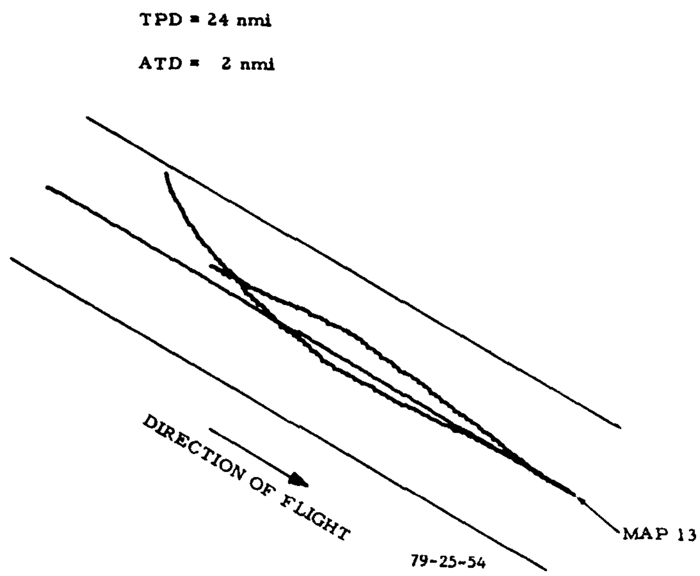

FIGURE 54. APPROACH PERFORMANCE RUNWAY 13, SIE

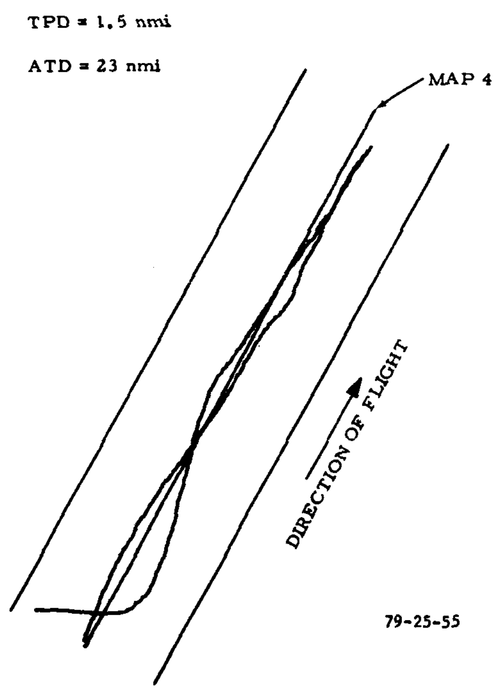

FIGURE 55. APPROACH PERFORMANCE RUNWAY 4, SIE

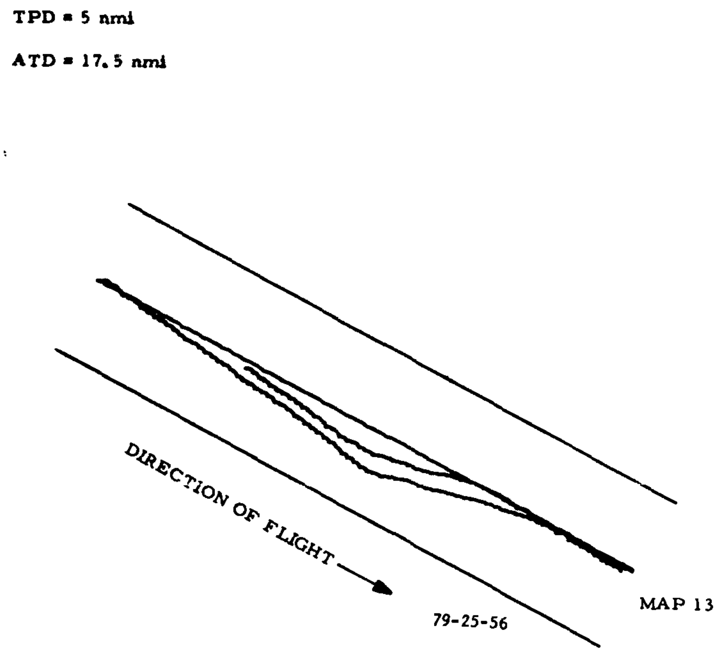

FIGURE 56. APPROACH PERFORMANCE RUNWAY 13, MIV

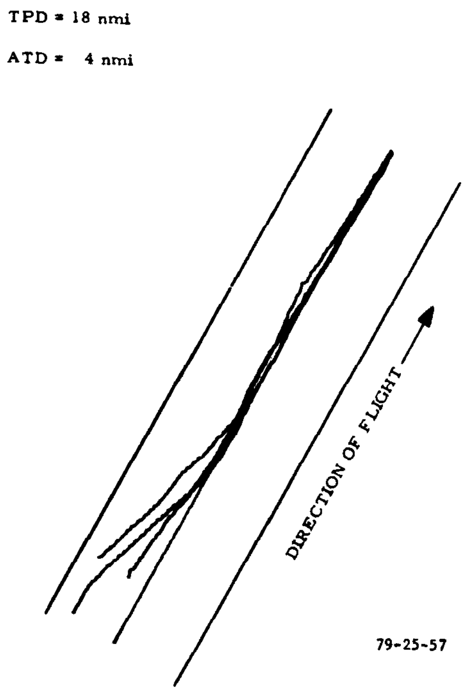

FIGURE 57. APPROACH PERFORMANCE RUNWAY 4, MIV

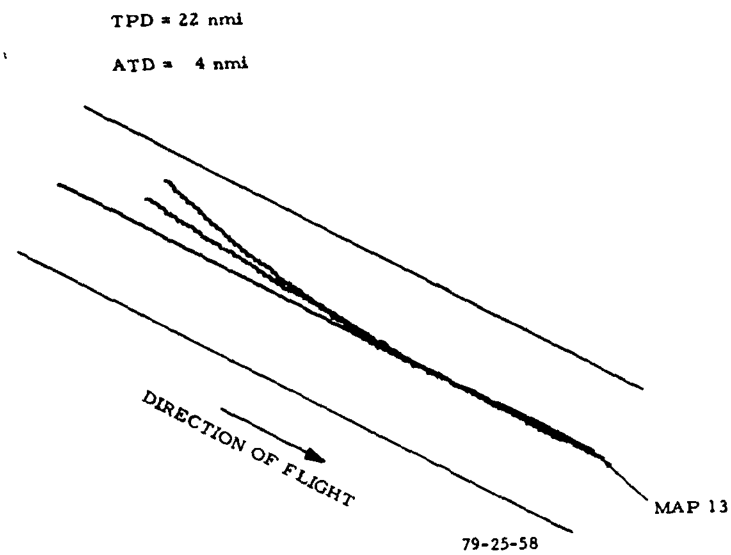

FIGURE 58. APPROACH PERFORMANCE RUNWAY 13, CYN

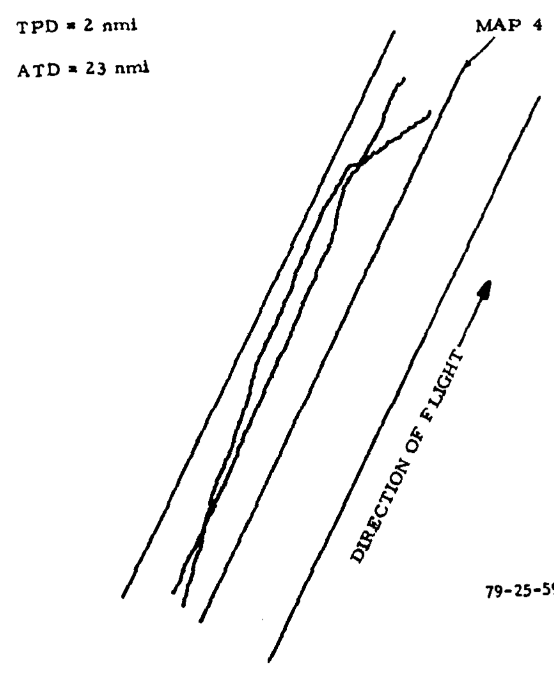

FIGURE 59. APPROACH PERFORMANCE RUNWAY 4, CYN

AD-A081 646   NATIONAL AVIATION FACILITIES EXPERIMENTAL CENTER ATL--ETC F/G 17/7
A FLIGHT INVESTIGATION OF SYSTEM ACCURACIES AND OPERATIONAL CAP--ETC(U)
FEB 80 J EDMONDS, J GALLAGHER, R PURSEL

UNCLASSIFIED FAA-NA-79-25 FAA-RD-79-120 NL

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APPENDIX

ERROR CALCULATIONS

By using latitude and longitude as the bases for all error computations, the number of computer subroutines was held to a minimum and a uniformity of error calculations resulted. Spherical earth computations were used throughout.

Initially, all errors were calculated referenced to a desired position (P_d) located on the desired track. The coordinate system was defined with the origin at P_d and with axes aligned with lines of latitude and longitude. After the computation of the error values in X and Y coordinates referenced to this coordinate system, a coordinate transformation was performed to align the error values into along-track and crosstrack components.

SUBROUTINES.

Most of the error calculations could be accomplished through the use of subroutines. These subroutines included: (1) bearing and distance computed from a pair of latitudes and longitudes, (2) a latitude and longitude computed from a bearing and distance from a given latitude and longitude, and (3) coordinate rotation to align errors with desired track.

HORIZONTAL ERROR CALCULATIONS—ORTHOGONAL DISTANCE-TO-WAYPOINT PROJECTION.

All error calculations were based on a projected position of the aircraft on the desired track. Since the actual position of the aircraft was not always on the desired track, an orthogonal projection of the actual aircraft position on the desired track was needed. The first step in this process was to use subroutine number 1 to compute bearing and distance between the two waypoints which define the segment. Then the same subroutine was used to compute bearing and distance from present position (actual position derived from EAIR) to the "TO" waypoint. The difference in the bearings from the TO waypoint was all that was needed to calculate the orthogonal projection of the actual track on the desired track. The projection was equal to the distance from the actual position to the TO waypoint times the cosine of the bearing difference (figure A-1). This distance was then used as an index on the parameter tape. Error values were calculated at 0.1-nmi increments of this distance.

SENSOR ERRORS.

After obtaining the distance-to-waypoint increment, sensor errors were calculated. Latitudes and longitudes of the VOR/DME stations were determined by using a look-up table. When this was done, the actual bearing and ground range of the aircraft, relative to the station, was calculated by using subroutine number 1. This results in P_a and θ_a.

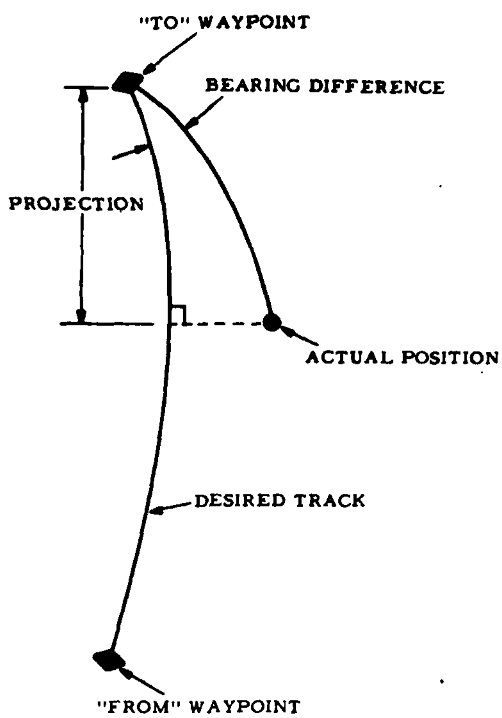

FIGURE A-1. ORTHOGONAL PROJECTION OF ACTUAL POSITION ON DESIRED TRACK

To find the total DME error, the measured slant range was first corrected to ground range.

$$\rho_s = [D_s^2-(H_a-H\theta)^2]^{1/2}$$

The total DME error was then

$$\Delta_\rho = \rho_s-\rho_a$$

VOR error was calculated in a similar way. Total bearing error was then

$$\Delta\theta = \theta_s-\theta_a$$

For the purpose of establishing system errors, a sensed position was calculated based on the VOR/DME information. The sensed position was calculated (by subroutine number 2) from sensed bearing and corrected ground range.

$$P_s(X) = f(\theta_s, \rho_s, \text{ and VOR/DME station position})$$

The next value computed was the RNAV computer position. RNAV computer position (P_c) was computed (using subroutine number 2) from the bearing-to-waypoint (BTW) and distance-to-waypoint (DTW) output from the RNAV computer, as well as the latitude and longitude of the waypoint.

$$P_c(X) = f(\text{BTW, DTW, and waypoint latitude and longitude})$$
$$P_c(Y)$$

Flight technical error was defined as the amount of deflection of the RDI.

$$FTE = RDI \text{ (nmi)}$$

Error values were then computed from these previously computed positions as follows: Sensed position error was computed from

$$\text{Sensor }(X) = P_s(X) - P_a(X)$$
$$\text{Sensor }(Y) = P_s(Y) - P_a(Y)$$

RNAV computer error was computed from

$$\text{COMP }(X) = P_s(X) - P_c(X)$$
$$\text{COMP }(Y) = P_s(Y) - P_c(Y)$$

Crosstrack total system error was computed from

$$\text{TS }(X) = P_d(X) - P_a(X)$$
$$\text{TS }(Y) = P_d(Y) - P_a(Y)$$

where P_d was previously computed (using subroutine 2) the bearing from the TO waypoint and the orthogonally projected distance on the desired track. By definition, P_d was on the desired track.

P_a is the actual aircraft position determined by the EAIR. The constants to convert from differences in latitudes and longitudes to nautical miles are deleted from the above equations.

COORDINATE ROTATION.

With all errors computed from latitudes and longitudes and expressed in nautical miles on a coordinate system with axes aligned with lines of latitude and longitude, a coordinate rotation was done to resolve the error measurements into crosstrack and along-track components. This was done by computing the desired track (θ_d) at the desired position (P_d) and performing a coordinate rotation. The desired track at P_d to the TO waypoint was computed using subroutine number 1. The new values (representing crosstrack and along-track values) were then $X_1 = X \cos \theta_d + Y \sin \theta_d$ and $Y_1 = Y \cos \theta_d - X \sin \theta_d$.

Table A-1 lists the signals recorded on the time merged parameter tape, as well as the values calculated for the error analysis.

TABLE A-1. PARAMETER TAPE FORMAT

THEEND		LAST RECORD IDENTIFIER	
ISEG		SEGMENT IDENTIFIER	
<u>IE DATA</u>			
	2	EAIR MONTH	
	3	EAIR DAY	
	4	EAIR YEAR	
	5	EAIR RUN NUMBER	
ITIME		AIRBORNE JULIAN DAYS	
IHR		AIRBORNE TIME RECORD	
IMIN		FROM TIME VALID	
ISEC		SIGNAL SOURCE	
IMS		MILLISECONDS	
<u>E</u>			
	1	EAIR LATITUDE (DEGREES)	
	2	EAIR LONGITUDE (DEGREES)	
	3	EAIR ALTITUDE (FEET)	
<u>PARAM</u>			
	1	LATERAL STEERING	A/D 1
	2	VERTICAL	A/D 2
	3	PITCH ATTITUDE	A/D 3
	4	ROLL ATTITUDE	A/D 4
	5	SPARE	A/D 5

6	SPARE	A/D 6
7	XTRK DEV	A/D 7
8	VTRK DEV	A/D 8
9-16	SPARE	A/D 9-16
17	SELECTED ALTITUDE	
18	SELECTED FLIGHT PATH ANGLE	
19	COMPUTED FLIGHT PATH ANGLE	
20	SELECTED XTRK DISTANCE	
21	XTRK DEV	
22	SELECTED ATRK DISTANCE	
23	TO/FROM ATRK	
24	FREQUENCY (BCD)	
25	VOR BEARING	
26	DME	
27	TRUE AIRSPEED	
28	HEADING	
29	BEARING TO WAYPOINT	
30	SELECTED WAYPOINT BEARING	
31	DISTANCE TO WAYPOINT	
32	SELECTED WAYPOINT DISTANCE	
33	STATION ELEVATION	
34	GROUND SPEED NORTH (FILTERED)	
35	GROUND SPEED EAST (FILTERED)	
36	SPARE	
37	VERTICAL PROFILE DEVIATION	

38	SPARE
39	SLANT RANGE CORRECTED DME
40	ONMI-BEARING SELECTOR
41	GROUND SPEED
42	TIME TO WAYPOINT
43	COARSE ALTITUDE
44	FINE ALTITUDE
45	DISTANCE NORTH
46	DISTANCE EAST
47	BARO ALTITUDE
48	SPARE

<u>DES</u>

1-9	SPARE
10	FROM
11	TO
12	TEST MODE
13	SPARE
14	REVERSION MODE
15	SPARE
16	VTRK FLAG
17	XTRK FLAG
18	NAV COMPUTER FLAG
19	DME FLAG
20	VOR FLAG
21	HEADING WARN
22	ALTITUDE WARN

23	TAS FLAG	
24-32	TUNING DISCRETES	

<u>CDU</u>

1	TEST	
2	AUTO TUNE VALID	
3	APPROACH MODE	
4	SPARE	
5	VNAV MODE	
6	ERASE	
7	ADEU	
8	RIGHT/+	
9	SPARE	
10	LEFT/-	
11	SPARE	
12	INCREMENT NAV WAYPOINT	
13	SPARE	

<u>A</u>

1	DTW	Orthogonal DTW Projection on Desired Track
2	P_1	Total DME Error (Ground Range)
3		Spare
4	θ-1	Total VOR Angular Measurement Error
5		Spare
6	$P_s(X)1$	VOR/DME/Sensed Position Latitude
7	$P_s(Y)1$	VOR/DME/Sensed Position Longitude
8		Spare
9		Spare

10	VDICT	Crosstrack (VOR/DME - Actual)
11	VDIAT	Along Track (VOR/DME - Actual)
12		Spare
13		Spare
14	COMPCT	(Computed - Sensed Crosstrack)
15	COMPAT	(Computed - Sensed Along Track)
16	FTCT	RDI (NMI)
17		Spare
18	TSCT	(Desired - Actual) Crosstrack
19	TSAT	(Desired - Actual) Along Track
20	OBSERR	(Actual - Desired)

AFLG (20) False = Invalid
True = Valid

13	SPARE
14	CHANGE NAV WAYPOINT
15	SPARE
16	INSERT
17	DISPLAY CHANGE
18	ENTRY
19	READ
20	CHANGE DISPLAY WAYPOINT
21	OFFSET MODE
22	SPARE
23	SPARE
24	XTRK
25	GS/TIME

26	ATRK
27	ALT
28	FPA
29	ELEV
30	FREQ
31	DIST
32	BEARING